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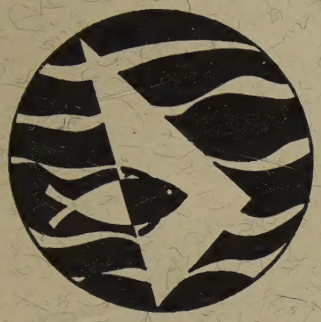

MANUAL OF METHODS FOR FISH STOCK ASSESSMENT

Part V. THE USE OF ACOUSTIC INSTRUMENTS IN FISH DETECTION AND FISH ABUNDANCE ESTIMATION

Edited by

B. B. Parrish

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Aberdeen, Scotland

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 1969

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PART V. THE USE OF ACOUSTIC INSTRUMENTS IN FISH DETECTION AND FISH ABUNDANCE ESTIMATION

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B.B. Parrish
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Rome, February 1969

PREPARATION OF THIS DOCUMENT

This forms an integral part of the FAO "Manual of Methods on Fish Stock Assessment". It is prepared by a group of experts on request by the Department of Fisheries. It is based on the Report of the Advisory Committee on Marine Resources Research (ACMRR) Working Party on Direct and Speedier Estimation of Fish Abundance, FAO Fish.Rep., (41) Suppl.1, of which the editor was convenor.

The present provisional version has been reproduced primarily for use at FAO and associated training centres, in FAO field projects and for limited distribution to specialists, on the basis of whose comments it is planned a revised edition will eventually be published in the official languages of FAO. The final revision will take into account experience in the use of the present version for training purposes, and will incorporate further advances in this field of research.

Distribution:

FAO Department of Fisheries
Regional Fisheries Offices
ICES Training Course on Acoustics
ICES
ICNAF

"Current Bibliography" entry:

Parrish, B.B. (Ed.) (1969) 15-5M012
FAO Fish.tech.Pap., (83):73 p.
Manual of methods for fish stock assessment.
Part 5. The use of acoustic instruments in
fish detection and fish abundance estimation.

Physics of acoustics. Acoustics methods.
Fish detection. Identification of records.
Echo counting. Abundance estimation.
Co 10-12835.

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CHAPTER 1

PHYSICAL PROPERTIES OF SOUND IN WATER; ITS PROPAGATION AND REFLECTION FROM TARGETS

L.M. Midttun

1. PROPAGATION OF SOUND

1.1 Formation of sound waves

Sound is produced if a material surface vibrates in a compressible medium such as water or air. The vibrating surface is called the sound source. The simplest type of sound results from a regular forward and backward, harmonic vibration of the surface.

During the vibration of such a surface in water, the water particles in contact with the surface are displaced by it. When the surface is at rest the pressure exerted on the water particles in contact with it is the hydrostatic pressure, corresponding to the height of the water column lying above it, but when it begins to move it exerts an excess pressure on them, its magnitude being directly proportioned to the velocity of movement of the surface, i.e. $p = Ru$ where p = excess pressure u = velocity of movement, R = constant, referred to later. ..... (1)
Thus, the pressure will be zero at the points of maximum amplitude of displacement of the water particles, when their velocity is zero, and greatest at the point where they pass the "at rest" position, when their velocity is greatest. These variations in amplitude of displacement and excess pressure with time, of water particles in contact with a harmonically vibrating surface are shown diagrammatically in Figure 1.

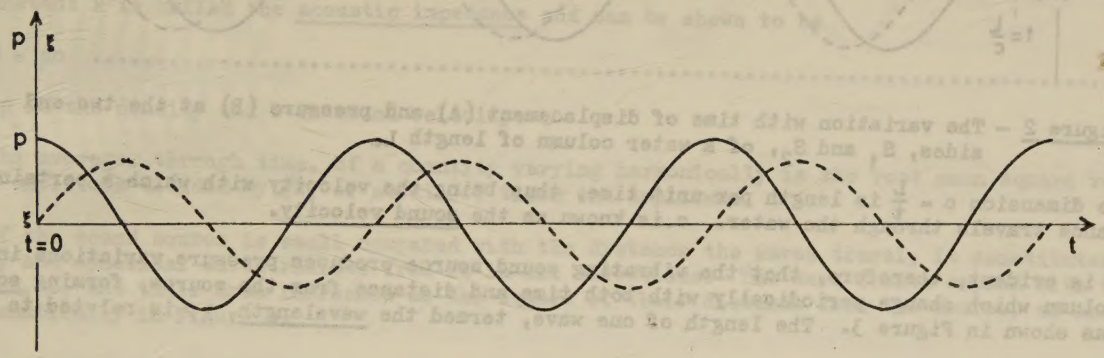


Figure 1 – Particle displacement, ξ, and pressure, p, as function of time, t, at the sound source, resulting from a harmonic vibrating material surface.

This shows that a new cycle of vibration commences when the vibrating surface returns to its original starting position having passed the points of maximum displacement on either side of it. The number of such cycles completed in unit time is called the frequency of the sound source, and is measured in cycles per second (c/s or Hertz; Hz). One thousand cycles per second is expressed as 1 Kc/s or 1 kHz.

The above conditions apply to the situation at the face of the vibrating surface. It is necessary next to consider the effect of the vibrating surface on the water particles at increasing distance from it.

Let us consider a column of water of length L and with unit cross sectional area placed with one end, S_1, on the vibrating surface, the other end being S_2. Now, when the surface moves forward, a pressure, as already described, acts on the surface S_1. Two effects follow: first, since the water is compressible, the pressure will cause a reduction of L, and second, the whole element is moved forward. As long as the speed of the surface increases, the pressure on the side S_1 also increases and the compression will continue. The side S_2 of the element is therefore moved forward at a somewhat lower velocity than the side S_1. As soon as the speed of the vibrating surface decreases and accordingly also the pressure, a small increase in element length, L, takes place and the surface S_2 now moves quicker than does S_1.

In other words a lag or delay in the movement of the surface S_2 as compared to the vibrating surface (and S_1), results from the property of compressibility as illustrated in Figure 2A. Hence, it follows that pressure variations at S_2 are also delayed behind those at S_1 (Figure 2B), the time of delay being $t = L/c$ where c is constant.

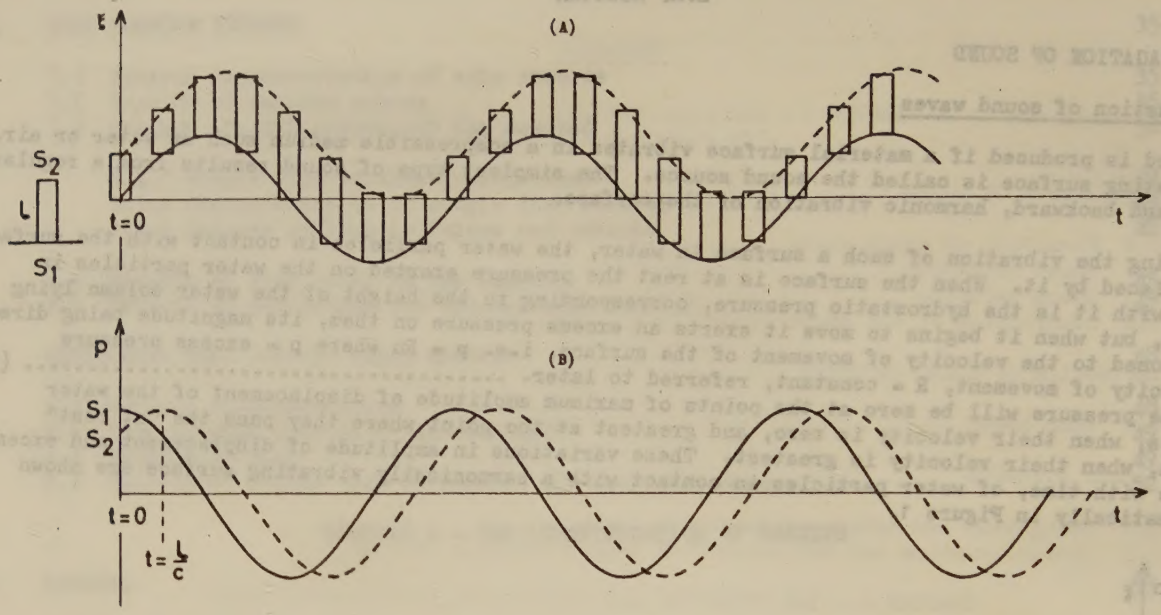


Figure 2 - The variation with time of displacement (A) and pressure (B) at the two end sides, S_1 and S_2, of a water column of length L.

The dimension $c = \frac{L}{t}$ is length per unit time, thus being the velocity with which a certain disturbance travels through the water. c is known as the sound velocity.

It is evident, therefore, that the vibrating sound source produces pressure variations in the water column which change periodically with both time and distance from the source, forming sound waves, as shown in Figure 3. The length of one wave, termed the wavelength, λ, is related to the

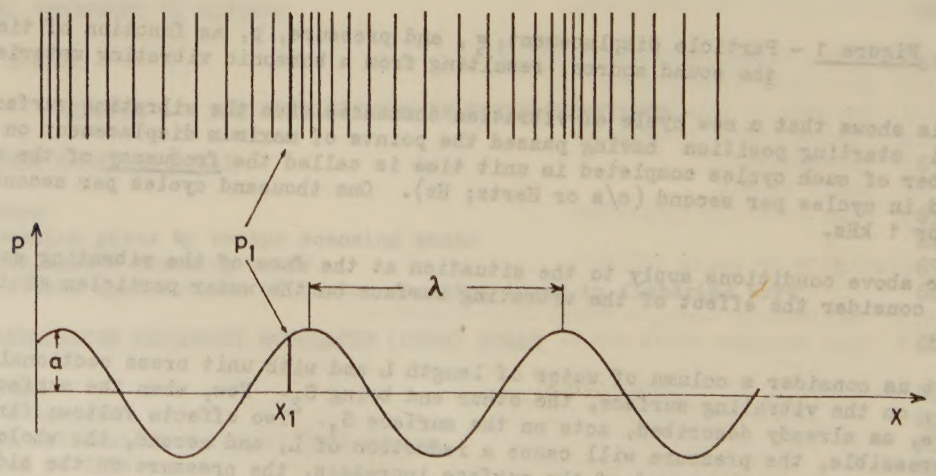


Figure 3 - The distribution of pressure at a certain time along the normal to a plane sound source of infinite size. (Amplitude, a, wavelength, λ, and wave front, p_1, at a distance x_1 are indicated)

frequency, f, of the sound source and the sound velocity, c, by the well known relationship

$$\lambda = \frac{c}{f} \quad \ldots\ldots (2)$$

1.2 Sound intensity

During the propagation of sound waves the energy transmitted by the vibrating sound source acts on the water column in two ways, i.e. by causing pressure changes within it and by displacing it forward and back. Acoustic energy is measured in terms of sound intensity, I, which, by definition, is the amount of energy which crosses a unit area, normal to the direction of propagation of the sound waves, in unit time. Since energy is defined as work (force x distance) per unit time, it follows that sound

$$\text{intensity} = \text{average (through time) of } \frac{\text{force}}{\text{time}} \times \frac{\text{distance}}{\text{cross sectional area}}$$

$$= \text{average of } \frac{\text{force}}{\text{cross sectional area}} \times \frac{\text{average of distance}}{\text{time}}$$

Since force per unit area is the same as pressure, and distance per unit time is velocity, sound intensity = average pressure x average particle velocity.

Thus, $I = \bar{p}.\bar{u}$ $\quad \ldots\ldots (3)$

Where I is the intensity and the bar denotes the time average of pressure p and particle velocity u equation (3) combined with (1) gives

$$I = \frac{\bar{p}^2}{R} \quad \ldots\ldots (4)$$

The constant R is called the acoustic impedance and can be shown to be

$$R = \rho c \quad \ldots\ldots (5)$$

where ρ is the density and c is sound velocity.

The average, through time, of a quantity varying harmonically is the root mean square value, which is the amplitude divided by $\sqrt{2}$, or about 0.7 times the amplitude.

If the sound source is small compared with the distance the waves travel, it constitutes a point source, and spherical waves radiate from it in all directions. The wave fronts expand with the velocity of sound, c, and their area increases as the square of their distance from the source, as shown diagrammatically in Figure 4.

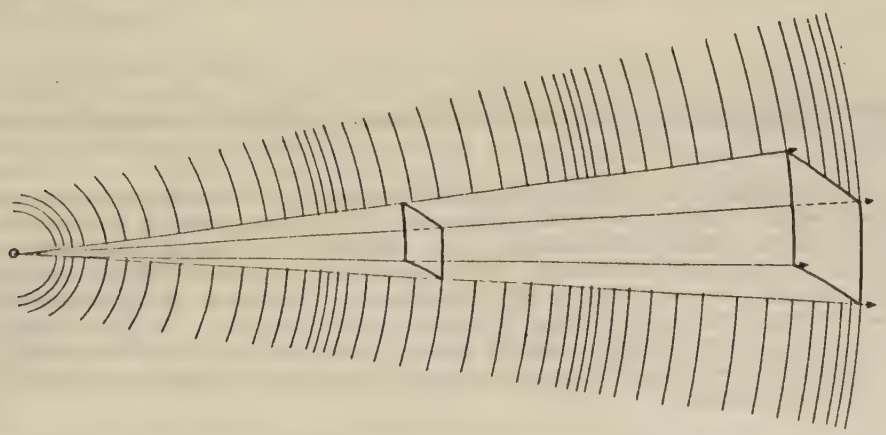


Figure 4 – The area of a wave front surface within a certain solid angle increases proportionally to the square of the distance from the source.

It follows, therefore, that the sound intensity, I, must decrease accordingly with distance from the source, and is given by the expression

$$I = \frac{1}{2\rho c} \cdot \left(\frac{a}{r}\right)^2 \quad \ldots\ldots (6)$$

where r = the distance from the sound source,

a = the amplitude of the pressure wave at unit distance from the source,

c = sound velocity,

ρ = water density.

Let us now consider two point sources vibrating at the same frequency. If the distance between them is one wavelength and the sources are vibrating together, the waves transmitted along the line connecting them will interfere constructively and be in phase, producing a reinforced wave, as shown in Figure 5A. Figure 5B, on the other hand, shows that if the distance between the sources is one half wavelength, the two sets of waves will interfere destructively and will be out of phase. The total sound field around the two sources is illustrated in Figure 5C, which shows that in some directions the waves are in phase and in others out of phase.

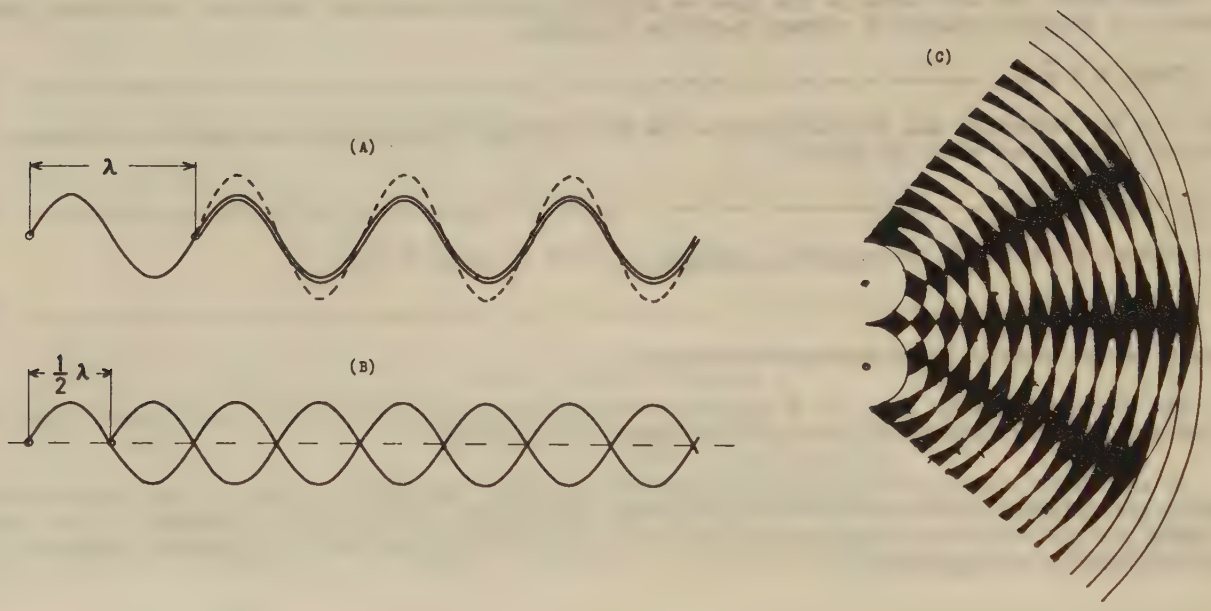


Figure 5 – Schematic illustration of interference between sound waves originating from two sound sources.

With sonar, it is necessary to operate with directed sound, the sound energy being transmitted within a well defined beam. This is achieved by the use of a plane, usually rectangular electro-acoustic oscillator (usually termed a Transducer – see Chapter 2), having sides which are longer than the wavelength of the transmitted sound. The face of the transducer can be regarded as consisting of many point sound sources, transmitting in all directions. The sound waves generated by them interfere with each other so that the sound intensity varies with direction. In the direction perpendicular to the transducer surface all of the waves are in phase, resulting in a maximum sound intensity in this direction, but at angles to the side of the perpendicular the sound intensity gradually decreases. At an angle θ_1, given by the relation

$$\sin \theta_1 = \frac{\lambda}{L} \qquad (7)$$

(where L = length of the side of the transducer) the sound intensity must be a minimum, since the waves from the different point sources moving in this direction are out of phase (see Figure 6). At a greater angle, a weaker secondary maximum, termed a side-loop, is found, and at a still larger angle θ_2, given by $\sin \theta_2 = 2 \frac{\lambda}{L}$, another minimum is found.

The distribution of sound energy transmitted in different directions can be described by a directivity pattern function $b = b_{(\Theta,\phi)}$ ..... (8)

where the angle Θ is the angle from the perpendicular to the transducer and ϕ the angle from a certain reference direction within its plane, as shown in Figure 7. If $I(0,0)$ is the intensity of sound transmitted in the direction perpendicular to the transducer, termed the acoustic axis, and $I(\Theta,\phi)$ the intensity in the direction (Θ,ϕ), then

$$b = b_{(\Theta,\phi)} = \frac{I_{(\Theta,\phi)}}{I_{(0,0)}} \quad \text{..... (9)}$$

b is, therefore, a quantity varying between 0 and 1.

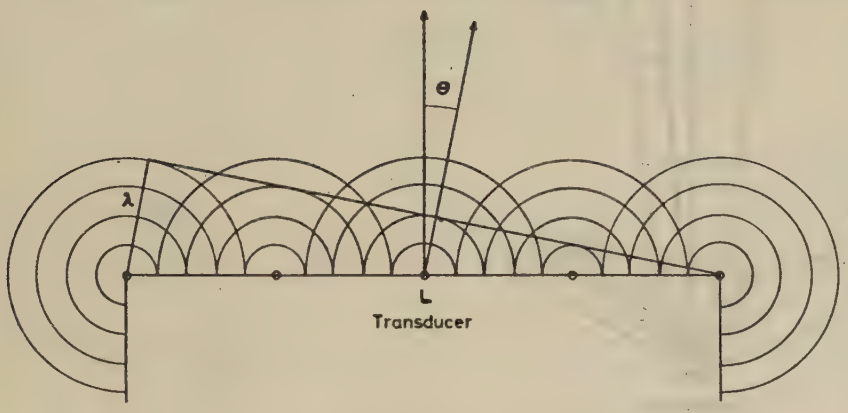


Figure 6 – Sound transmission from a transducer. At an angle Θ from the normal, there is a phase difference of $\frac{\pi}{2}$ i.e. $\frac{\lambda}{4}$ between the neighbouring point sources here indicated.

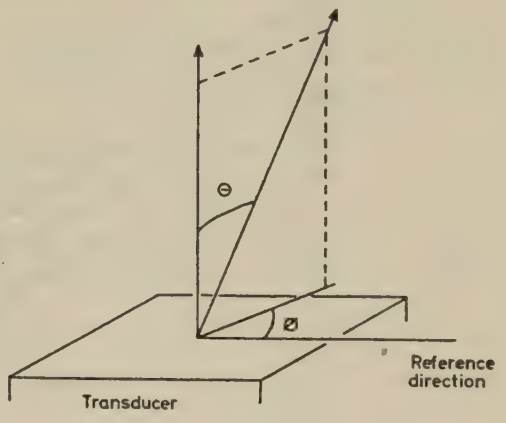


Figure 7 – Interpretation of the direction (Θ,ϕ).

Normally the directivity pattern function has to be found empirically for each particular transducer, but a good approximation can be obtained using the equation of diffraction

$b = \frac{\sin^2\beta}{\beta^2}$, where $\beta = \frac{\pi L}{\lambda} \sin\Theta$.

It is often convenient to operate in terms of amplitude of signal instead of echo intensity. This can be measured directly as voltage, because the amplitude of the acoustic signal is directly proportional to that of the electrical signal recorded in the receiver. This makes it necessary, however, to define another directivity coefficient, δ, which is the ratio of the amplitudes of the signal transmitted at an angle to the acoustic axis to that at the same range on that axis. It is seen from equation (6) that the echo intensity is proportional to the square of the amplitude. It is evident from equations (9) and (6) that

$$b = \frac{I_{\Theta,\phi}}{I_{0,0}} = \frac{\left(\frac{a}{r}\right)^2_{\Theta,\phi}}{\left(\frac{a}{r}\right)^2_{0,0}} = \frac{a^2_{\Theta,\phi}}{a^2_{0,0}}$$

Therefore $\delta = \sqrt{b}$.

The directivity pattern of a transducer is often represented by a polar diagram, usually referred to the two planes parallel to the transducer sides. An example is shown in Figure 8.

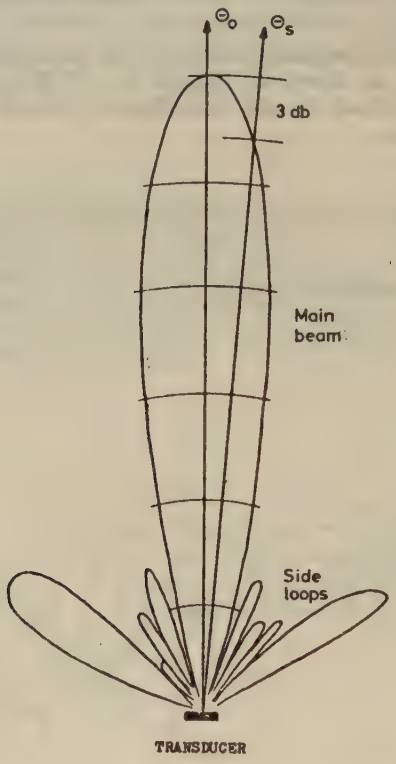


Figure 8 - A transducer's directivity diagram; Θ_o = acoustic axis; Θ_s = half value angle.

The unit used here is termed "decibel" (db), defined as 10 times the logarithm of $\frac{I}{I_o}$ where I_o and I are any two sound intensities.

It is convenient to be able to describe the directivity of a transducer by a single quantity, i.e. the directivity index D.

$$D = 10 \log \frac{1}{\frac{1}{4\pi} \int_\Omega b.d\Omega} \quad \ldots\ldots (10)$$

A common way of describing the width of the sound beam is to use the half value angle, Θ_S, the angle at which the sound intensity has dropped to half the value it has on the acoustic axis, i.e. the angle at which $b = \frac{1}{2}$ and $10 \log b = -3$db.

The sound intensity in the direction Θ_S is thus 3db below that on the acoustic axis. It is possible to a good approximation, to compute the angle Θ_S for a rectangular transducer by means of the formula

$$\Theta_S = \pm 25 \frac{\lambda}{L} \quad \ldots\ldots (11)$$

where λ is the wave length and L is the transducer side length in the same plane.

1.3 Sound velocity

It is possible to show that the velocity, c, with which sound waves travel in water is a function of the density and compressibility of sea water, as follows:

$$c = \sqrt{\frac{1}{\rho K}} \quad \ldots\ldots (12)$$

where ρ is the water density and K is its true compressibility. Alternatively it can be expressed in

terms of the elasticity E of the water, the inverse of its true compressibility. Thus,

$$c = \sqrt{\frac{E}{\rho}} \qquad (13)$$

The modulus of elasticity, E, is also known as the bulk modulus. As for sea water, both the density and the elasticity are functions of temperature, salinity and depth, and the velocity of sound can therefore also be expressed in terms of these variables

$$c = 1400 + 4.9t - 0.044t^2 + \left(1.32 - \frac{t}{100}\right) S + 0.018 \left(1 - \frac{t}{100}\right) d \qquad (14)$$

where t is temperature (C^o), S salinity (per mille) and d depth (metres). Values of velocity, derived from this equation are shown graphically in Figure 9.

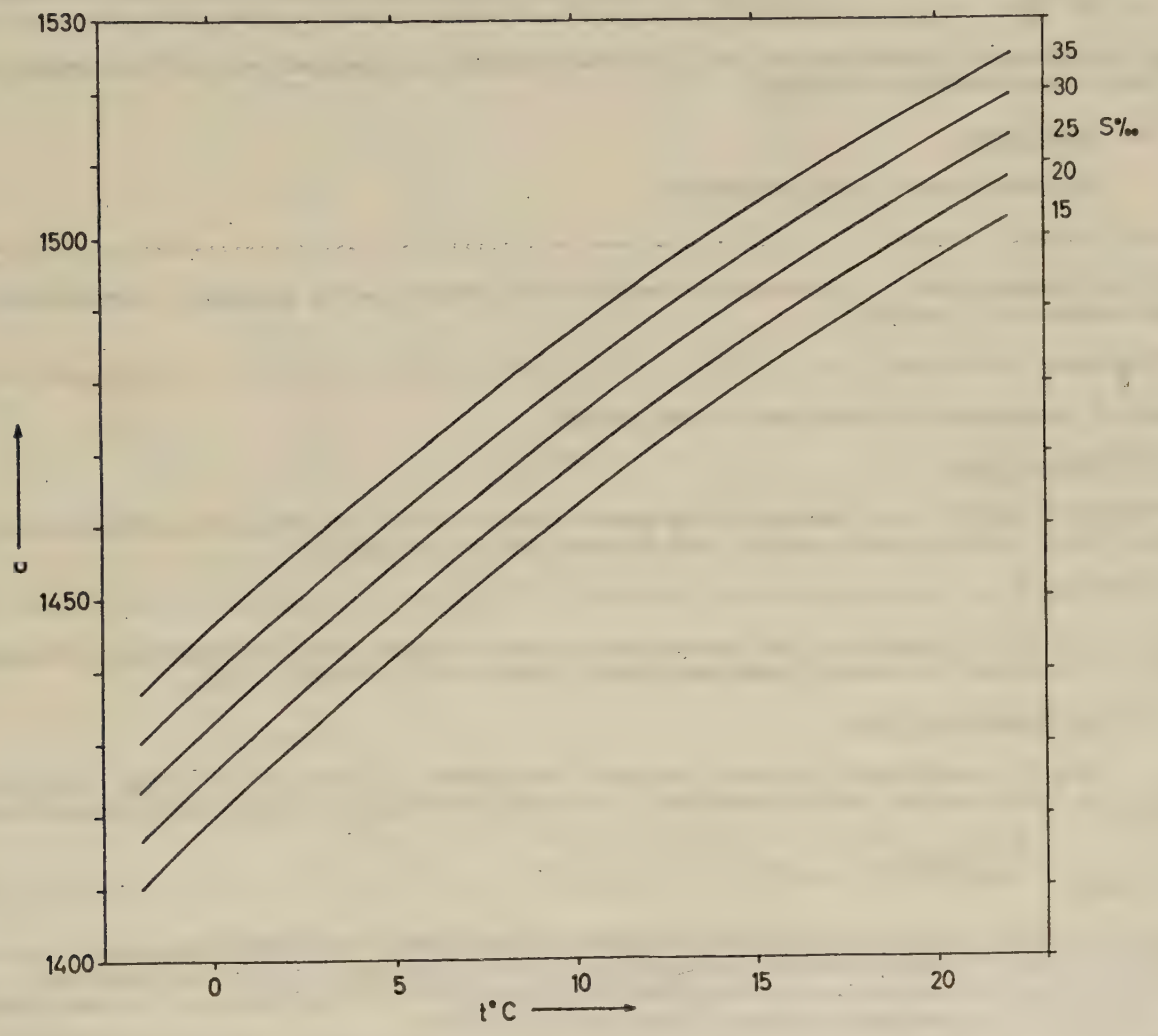


Figure 9 - Changes in sound velocity c, with changes in temperature, t^oC, and salinity $S^o/_{oo}$.

In sonar the sound is transmitted as sound pulses of a certain duration and sent at regular intervals. The duration of each pulse is called the pulse length τ (sec.), which therefore covers $c\tau$ metres of water.

1.4 Description of the sound field

We shall here sum up the properties describing the sound field and introduce the units which are convenient to use.

(a) Sound pressure, $\bar{p}$

As already shown, sound waves are described in terms of pressure disturbance, and normally as sound pressure, which is the root mean square value of the instantaneous sound pressure, or 0.7 times the pressure amplitude averaged over a few cycles. Sound pressure is reported in dynes per sq. cm (often the sound pressure is denoted just by p without the bar).

(b) Sound intensity

The sound intensity I, is the average power carried by a sound wave per unit cross-section of a wave front, and is measured in watts per sq. cm. The intensity is related to the sound pressure by the formula

$$I = 10^{-7} \frac{\bar{p}^2}{\rho c} \quad \ldots\ldots (15)$$

where I is intensity in watts per sq. cm, $\bar{p}$ is sound pressure in dynes per sq. cm, ρ is density in g/cm^3 and c sound velocity in cm/sec.

(c) Sound level

The sound level L is by definition

$$L = 10 \log \frac{I}{I_o} \quad \ldots\ldots (16)$$

where I is intensity and I_o is a certain reference value, adopted as the intensity corresponding to a sound pressure of 1 dyne/cm^2.

Therefore, $L = 20 \log \bar{p}$ ..... (17)

The unit of measurement of sound level is the decibel.

(d) Source level

The source level S, is a measure of the power output of a sound source on the decibel scale, or the sound level on the acoustic axis at unit distance from the transducer

$$S = 10 \log F \quad \ldots\ldots (18)$$

where F is the sound intensity on the acoustic axis at unit distance from the transducer. The source level of a transducer is normally found empirically by means of a microphone test.

(e) The sound field level

When the source level is known, the sound field level, L, at any point in the sound beam, expressed in decibel units, can be determined. The sound intensity at a point (r, θ, ϕ) within the beam is given by

$$I_{(r,\theta,\phi)} = \frac{F \cdot b_{(\theta,\phi)}}{r^2} \quad \ldots\ldots (19)$$

Where F is the sound intensity in the acoustic axis at unit distance from the transducer, b is the directivity pattern function expressed in equation (9), and r the distance from the transducer. (This formula is often called the inverse square law equation.) The sound level, L, is then found by taking ten times the logarithmic values of equation (19) so that

$$L_{(r,\theta,\phi)} = S + 10 \log b_{(\theta,\phi)} - 20 \log r \quad \ldots\ldots (20)$$

The above formula is only valid in a homogenous, non-dissipating medium. Since sea water is not such an ideal medium, another term must be added to the equation (20) viz. the transmission anomaly.

(f) Transmission anomaly

The transmission anomaly, A, is a quantity describing the drop of sound level during transmission through sea water additional to the geometrical spreading as described by the inverse square law. Thus

$$L_{(r,\theta,\phi)} = S + 10 \log b_{(\theta,\phi)} - 20 \log r - A \quad \ldots\ldots (21)$$

The transmission anomaly is caused by two groups of factors. The first one is called the attenuation at the sound due to absorption and scattering. The second is called the spreading anomaly and includes refraction but also reflection from boundary surfaces.

In vertical echo sounding, spreading anomaly can be disregarded and the transmission anomaly is caused by attenuation only, so that

$$A = \frac{\alpha r}{1000} \qquad (22)$$

where α is the attenuation coefficient, measured in decibels per kilometre and r is the distance in metres. The attenuation of sound in water increases with increasing transmission frequency, and it also varies from place to place and time to time due particularly to changes in the scattering properties of sea water. Some average values are given in Figure 10.

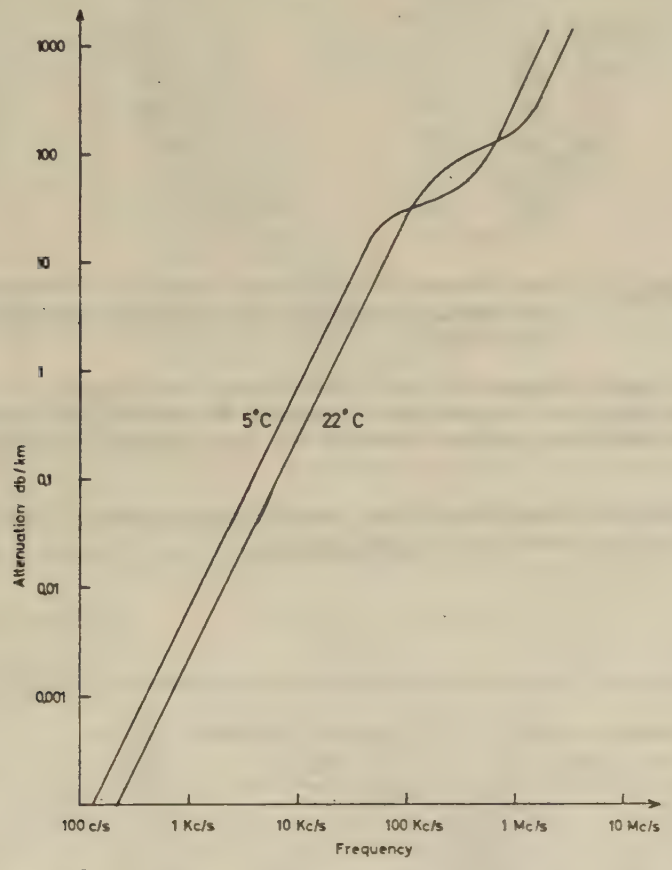


Figure 10 – Changes in the attenuation coefficient for sound in the sea, with increasing transmission frequency at 5°C and 22°C.

Often the drop in sound level caused by both geometric spreading and transmission anomaly is called the transmission or propagation loss, H, which is therefore given by

$$H = A + 20 \log r \qquad (23)$$

Spreading anomaly becomes important in horizontal echo ranging, due to the refraction of the sound beam. It has already been shown that the velocity of sound varies with temperature, salinity and depth. The greatest variations of sound velocity are caused by variations in temperature, which are often rather large vertically. If the velocity of sound decreases with depth, the upper part of a wave front will travel faster than the lower part. This will cause the advancing sound beam to be deflected as shown in Figure 11. In the same way a positive velocity gradient results in an upward deflecting beam.

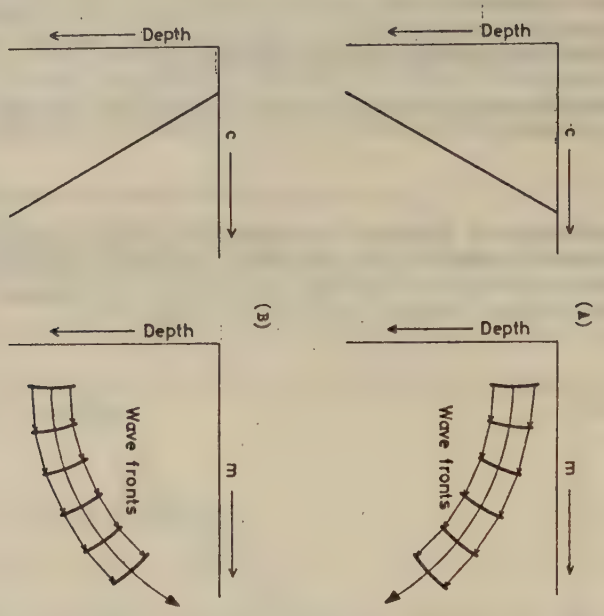


Figure 11 - The refraction of a sound beam; A = velocity decreasing with depth; B = velocity increasing with depth.

If the beam angle of sound transmitted from a horizontal echo ranger and the variation with depth of the sound velocity are known, it is possible to compute the sound field conditions. In Figure 12 are shown four typical transmission patterns constructed from measured velocity conditions in a locality off the coast of Norway.

In and below a temperature discontinuity the transmission anomaly A will be large resulting in poor sonar conditions. This is known as the layer effect.

Figure 12 (A)

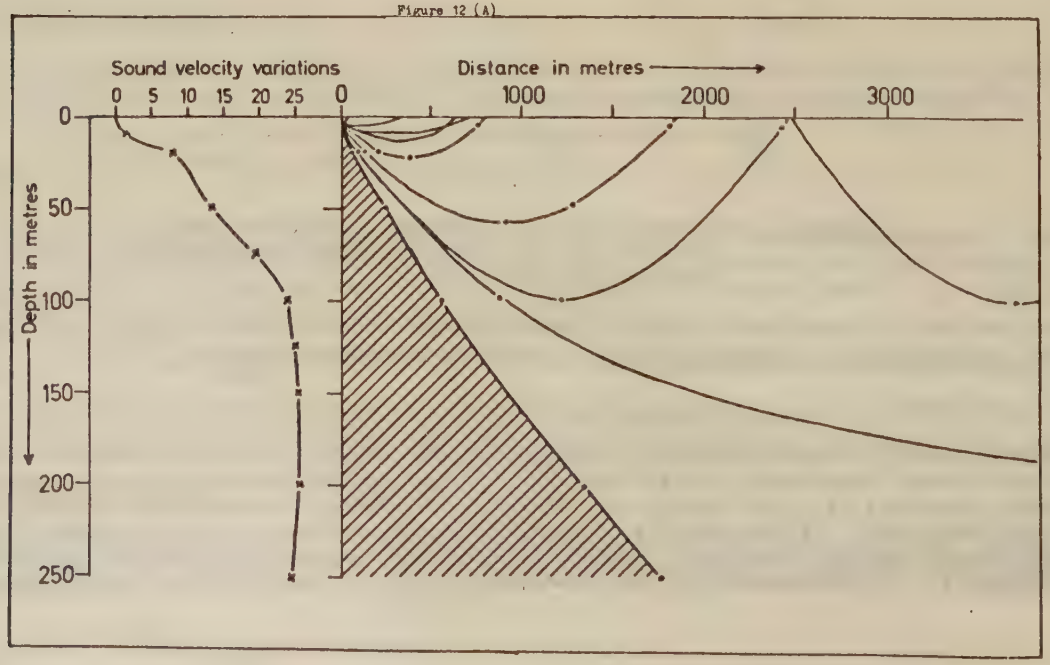


Figure 12 (B)

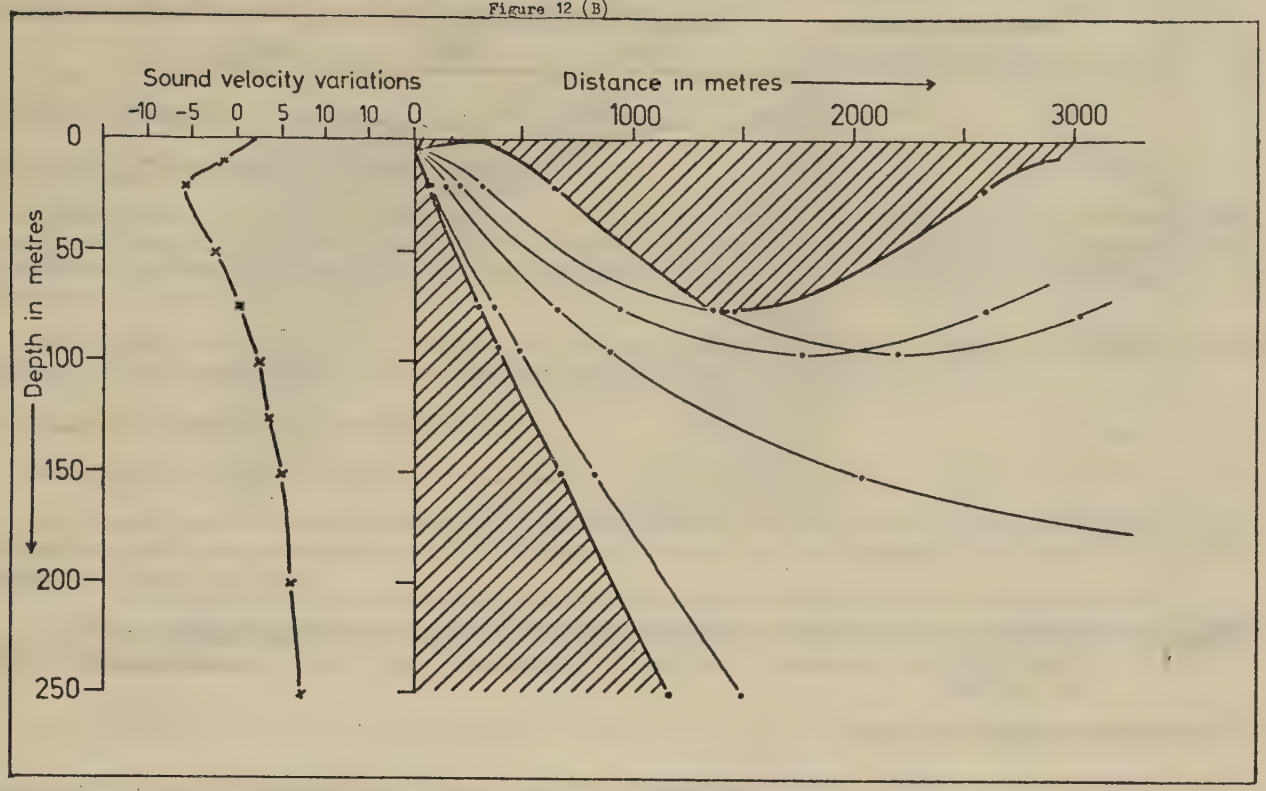


Figure 12 (C)

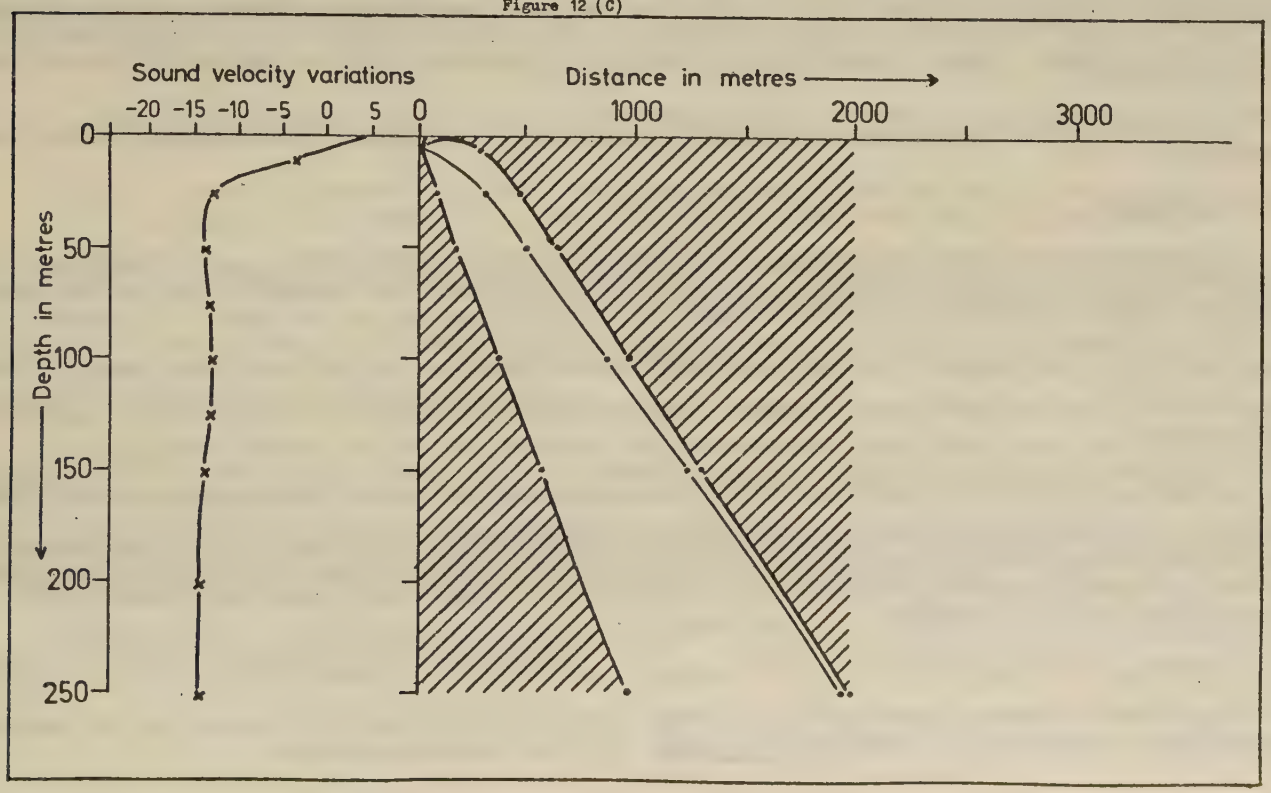


Figure 12 (D)

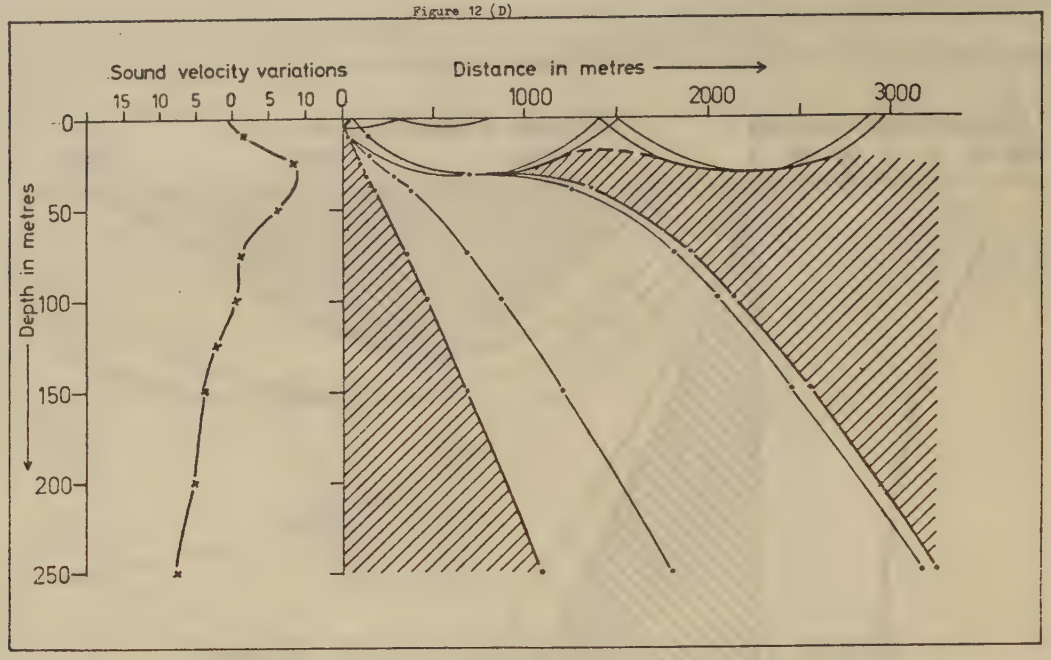


Figure 12 - Four typical sound beam transmission patterns computed from measurements of temperature and salinity. Beam half value angle, $\Theta_s = \pm 12.5^{\circ}$. Shadow zones are hatched.

2. REFLECTION OF SOUND IN WATER

If we shout against a steep cliff or a mountain side we get an echo because the sound of our voice is reflected from the wall and reaches our ears. When the sound waves reach the wall, the wall obstructs the movements of the air particles. The wall exerts a counter pressure on the vibrating air particles equal to the pressure of the particles on the wall. In fact, the wall itself becomes a source of sound, transmitting sound waves counter to those reaching it. These waves transmitted by the wall constitute the reflected sound. The whole process may be compared to what happens when a rubber ball bounces back from a brick wall.

In a similar way sound is also reflected in the sea by the sea bed and other targets, such as fish or shoals of fish.

2.1 Echo level

When sound is reflected by a target, the intensity of the reflected sound, I_e, is proportional to the intensity of the incident sound I_i. If the reflected sound intensity is measured at a distance r from the target, according to the inverse square law we have

$$I_e = k \frac{I_i}{r^2} \quad \ldots\ldots\ldots\

$$E_{(\theta,\phi)} = 10 \log k + S + 20 \log b_{(\theta,\phi)} - 2H \quad \ldots\ldots (27)$$

For echoes on the acoustic axis the formula is reduced to

$$E_{(0,0)} = 10 \log k + S - 2H \quad \ldots\ldots (28)$$

3. TARGET STRENGTH

3.1 Definition and nature of target strength

The quantity 10 log k in the above equations is called the target strength, T, and is dependent on the size and other characteristics of the target. The reflection strength of the target can also be expressed by another quantity, called the effective target area or scattering cross section, σ, and defined as follows:

"If an echo was reflected by a total reflecting target with uniform spherical reflectivity pattern, the area of this target normal to the incident sound would be equal to σ".

T and σ are related by the expression

$$T = 10 \log \frac{\sigma}{4\pi} \text{ ; where } \frac{\sigma}{4\pi} = k \quad \ldots\ldots (29)$$

It is seen that a totally reflecting sphere of radius 2 m has a target strength of 0 decibels, because the scattering cross-section of this sphere is equal to 4π. The target strength of an object depends on several factors:

(a) The acoustic impendance of the target in relation to that of water, expressed by the index of reflection, μ

$$\mu = \frac{R_1 - R_2}{R_1 + R_2} \quad \ldots\ldots (30)$$

where $R = \rho c$ is the impedance and 1 and 2 indicate water and target.

(b) The size of the target in relation to the wavelength of sound. If the size is described by a parameter, l, and the wavelength by λ, one can distinguish between three magnitudes of this relation.

(i) when $\lambda \ll l$ the target strength can be found by using laws of geometric optics.

(ii) when $\lambda \gg l$ (the so-called Rayleigh scattering zone) the scattering cross-section can be shown to vary inversely with the fourth power of the wavelength.

(iii) in the intermediate zone where wavelength and target size are similar, the target strength is dependent on the size, geometry and orientation of the target.

The sizes of most fish in which we are interested are within the range 10 and 100 cm. Since at very low frequencies (<10kHz) the noise level is often too high, and at very high frequencies (>100kHz) the attenuation is high for general fish detection purposes, it is the middle zone of frequencies that is usually chosen for equipment. Theoretically the target strength of a given fish should increase with frequency, but there are not yet enough observations to establish the relationship between target strength and fish size, at different frequencies.

The transition between the Rayleigh zone and the "middle" zone takes place when the dorsal-ventral dimension of the fish (which at its maximum is approximately 0.2 of the total length) approaches that of the wavelength (Haslett, 1962a). Figure 13 shows the relation between the scattering cross-section and frequency in the two zones for fish of 90 cm, 45 cm and 22.5 cm length. The data, which are taken from Haslett (1962b and 1964) show that entry into the middle zones is characterized by a series of maxima and minima, the trend of the maxima being indicated by the broken line.

The pulse length of the transmitted sound is of importance only when the length of the pulse in water τc is small compared to the target size.

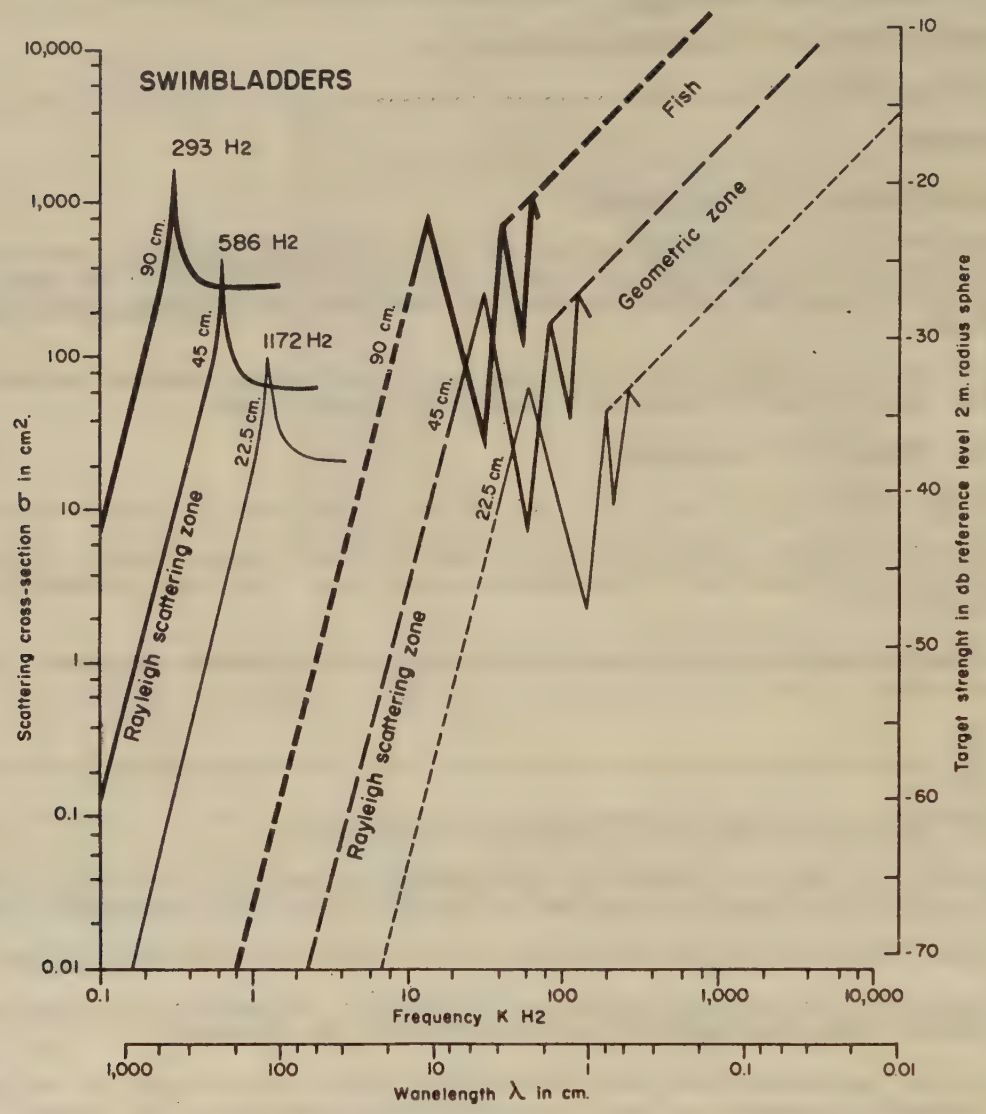


Figure 13 - The relationship between target strength and transmission frequency for fish of 22.5 cm, 45 cm and 90 cm length respectively.

3.2 Characteristics and measurement of target strength of fish

(a) Single fish targets

Although some direct measurements of target strengths of fish have been made, considerably more data are needed in order to establish a satisfactory law for sound reflection by fish of different species and size.

Measurements of target strength have been made by Hashimoto and Maniwa (1956), Midttun and Hoff (1962), Cushing et al. (1963) and by Shishkova (1963). The measurements obtained are very variable but those of Midttun and Hoff (1962) show the relation between target strength and length of fish most clearly. In their experiments, the fish were kept alive at testing depths for a week and then killed just before the measurements were made. Figure 14, reproduced from Cushing (1964), summarizes some of the measurements obtained by these and other workers (Harden Jones and Pearce, 1958; Cushing et al., 1963).

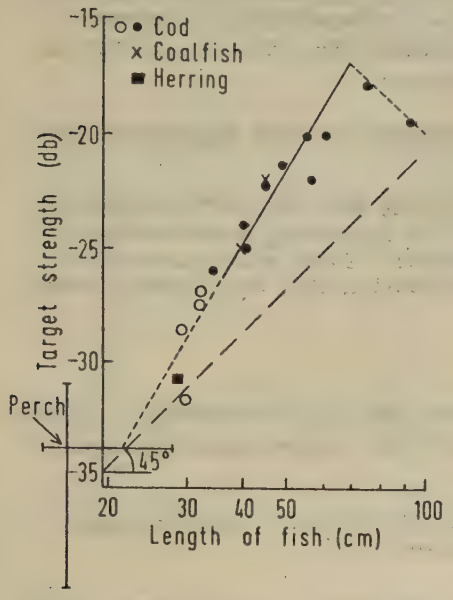


Figure 14 – Measurements of Target strength of cod, coalfish and herring; after Cushing, 1964.

It will be seen that as length of fish increases its target strength increases as nearly the cube of the length, indicating that it bears some relation to the volume of the fish. But the relation is not a simple one, due to the different sound reflecting properties of different parts of the fish. The signal is returned in varying proportions from bones, flesh and air bladder (Haslett 1962). Harden Jones and Pearce (1950) have shown that the swim bladder is responsible for about half the signal returned from those species of fish which possess one. Also the target strength varies with the aspect of the target, the lateral aspect returning ten times as much signal and the dorsal aspect under some conditions (Harden Jones and Pearce, 1958; Haslett, 1964). However, at any intermediate aspect there are a number of minima, differing with sizes and species of fish (Haslett 1962, Midttun and Hoff 1962). Haslett (1964) provides a good summary of the physical basis of echoes received from fish targets. In estimating abundance from echo survey records, it is assumed that fish targets, on average, present their dorsal aspects to the transducer.

It is useful to note two methods of estimating signal strength of fish targets at sea conveniently measured in amplitude or voltage; (a) a fish crosses the beam, entering it and leaving it at extreme range, but at a mid-point on its track across the beam the range is least. At this point, the signal is maximal; (b) at the same time, the duration of the trace is related to the signal strength in some restricted circumstances. It is possible, with an echo chart of individual traces in a layer, to make relative estimates of sizes by depth within the layer (Cushing 1967). Given a calibrated echo sounder with an apparatus for estimating amplitude and another for recording duration of individual targets, two independent methods are available for estimating signal strengths of individual targets.

Many fish of commercial importance have swimbladders, occupying about 7 and 5 per cent of the body volume in freshwater and marine species respectively, which can enhance the echo to give scattering cross-sections much greater than those which would be observed in its absence. There is also the possibility of an added bonus by way of resonance. If the swimbladder is regarded as a spherical bubble, its scattering cross-section can be considered as having three major regions. At low frequencies, the Rayleigh scattering, or fourth power law, is obeyed: at resonance the scattering cross-section is independent of bubble size, and at higher frequencies the scattering cross section, σ, is independent of frequency and equal to the bubble surface area; i.e. $\sigma = 4\pi R^2$.

The resonant frequency of the swimbladder can be determined from the formula

$$f_r = \frac{1}{2\pi a}\sqrt{\frac{3\gamma P_o}{\rho}} \quad \ldots\ldots (31)$$

where a = radius of a sphere of same volume as the swimbladder,

γ = ratio of specific heats of gases,

ρ = density of water

P_o = the ambient pressure

Weston (1967) gives a simpler formula from which the resonant frequency of a swimbladder can be calculated for a fish or given length and living at a given depth (or pressure). In Weston's formula

$$f_o L = 8\sqrt{P_o} \quad \ldots\ldots (32)$$

where f_o = resonant frequency in kHz

L = fish length in cm, and

P_o = ambient pressure in atmospheres

Weston (1967) also gives a simple formula to calculate the scattering cross-section of the swimbladder in the region above resonance, where the values are more or less independent of frequency, depth and various sources of loss. In this formula $\sigma = 4 \times 10^{-2} L^2$ giving, for a 90, 45 and 22.5 cm fish, scattering cross-sections of 320 cm^2, 80 cm^2 and 20 cm^2 respectively.

There is some uncertainty as to what increase in scattering cross-section might be obtained from the swimbladder, at resonance, within the body of the fish.

Scattering cross-sections of swimbladders for 90, 45 and 22.5 cm fish are included in Figure 13, the resonance frequency being calculated for a depth of 50 fathoms. The scattering cross-section at resonance has been taken as five times that in the region above resonance. These values are only estimates, but they do serve to show the increase in scattering cross-section that could result from the presence of the swimbladder.

(b) Multiple fish targets

Given two targets at distances r_1 and r_2 from the transducer, they will be recorded as single echoes so long as $r_1 - r_2 > \frac{1}{2}\tau c$. In the case $r_1 - r_2 < \frac{1}{2}\tau c$ their individual echoes cannot be distinguished and the received signal is a multiple echo.

If all single fishes in a multiple fish echo are contributing equally and with the same target strength as they do as single fishes, the multiple echo intensity, M, would be

$$M = \sum I_e b^2 \quad \ldots\ldots (33)$$

If all of the fish have the same target strength, this can be substituted by

$$M = n I_e \bar{b}^2 \quad \ldots\ldots (34)$$

where n is the number of fish, I_e is the echo intensity received from a single fish at the same distance and $\bar{b}$ is the mean directivity coefficient of the fish detected.

The number of fishes could then be found from the equation

$$10 \log n = 10 \log M - S - T + 2H - 20 \log \bar{b} \quad \ldots\ldots (35)$$

where 10 log M is the received multiple echo level, S the source level, T target strength of an individual and 2H the transmission loss during two-way propagation.

This method is likely to give an underestimate of the number of fishes for a given echo intensity for densely shoaling species, because each fish would not contribute in full strength under such circumstances.

An empirical relationship between the multiple target strength and the number of scatters in shoals of Atlanto-Scandian herring in the Norwegian Sea has been established by Truskanov and Scherbino (1964).

CHAPTER 2

THE STRUCTURE AND FUNCTIONING OF SONAR EQUIPMENT

R.B. Mitson

1. BASIC FEATURES OF SONAR EQUIPMENT

A sonar system comprises the four basic units shown diagrammatically in Figure 15.

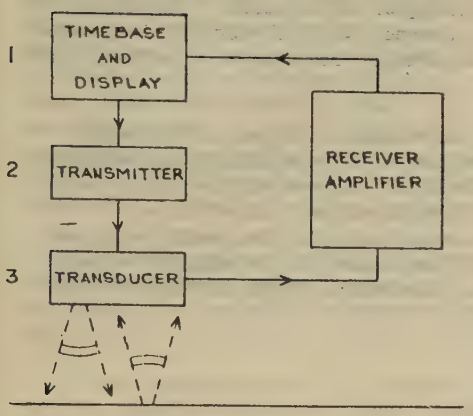


Figure 15 – Block diagram of basic echo sounder system.

In this diagram, Block 1 is the timebase and display unit. Block 2 is the transmitter which is connected to Block 3, the transducer. From this, received signals go to Block 4, the receiver amplifier, and from it to the display unit. The timebase and display unit may be an electric motor driving a mechanical system for marking a recording paper, or an electronic circuit controlling the speed at which a spot of light travels across the face of a cathode ray tube. In either case accuracy of timing is important, for an error of $\pm$ 1.5 x 10^{-3} sec would give a depth or range error of $\pm$ 1 m.

At one point on its travel the arm on the mechanical system, or the spot on the cathode-ray-tube, will pass the zero mark on the depth or range scale and at this instant of time the transmitter (Block 2) is switched on by the timebase and its energy is released to the transducer (Block 3). The transducer converts electrical energy to acoustic energy which is propagated through the water. In most modern equipment the same transducer receives the echo from a distant object or sea bed, converting it back from an acoustic to an electric signal.

It has been shown in Chapter 1 that the echo has only a fraction of the energy of the transmitted pulse. The receiver amplifier (Block 4) is necessary to increase this weak signal by perhaps a million times to mark the recorder paper or deflect the cathode-ray-tube spot.

While the basic principles underlying the vertical echo sounder and the horizontal echo ranging sonar are essentially the same, the two types of equipment differ in some important respects. Therefore, in the following description of the features and functioning of the main units as defined above, attention is first paid to the echo sounder. The special features of sonar are then described.

2. ECHO SOUNDER

2.1 Timebase and display unit (Block Unit No. 1)

As mentioned above, the timebase – display unit may be either based on a mechanical or an electronic cathode-ray-tube system. The main features of each of these systems are described below.

(a) The mechanical paper system

Until recently ships have been supplied with direct current. As a result the motor driving the mechanical recording system is connected to the ship's mains supply which is probably 110 volts or 220 volts DC. In a small vessel, or where it is desirable to isolate the echo sounder from the mains supply, it is usual to have a 24-volt battery supply.

In both cases there is likely to be voltage variation which affects the speed of a direct current motor. The mains voltage depends upon the stability of the prime mover turning the generator. In the case of generators running off the ship's propeller shaft, stability is often very poor indeed, particularly in bad weather when the loading on the propeller varies greatly. Mains voltage variation causes the speed of the motor, and hence the accuracy of the timebase, to fluctuate. Where batteries are used the speed would be correct at the nominal 24 volts, but too great at perhaps 28 volts when the batteries are freshly charged and too low at 20 volts when discharged. A voltage change of 10% results in a speed change of 5% causing a similar scale error. This situation relates to DC motors of the shunt-wound type; these have the rotating winding (armature) electrically connected in parallel with the stationary winding (field). To obtain the required constant speed, governor controlled motors are used. A switch operated by centrifugal force is fitted on the motor shaft; when the motor increases speed above normal, the switch closes and increases the voltage across the field winding

causing the motor to slow. Conversely, when the motor speed is low the switch opens, reducing the field voltage and returning the motor to its correct speed. The mechanical construction of the centrifugal governor switch is quite complicated; it also requires regular checking and setting.

Manufacturers now use synchronous AC motors which are independent of voltage variations because their rotation is synchronous to the frequency (cycles per sec. or Hz) of the power supply. Their accuracy is therefore limited only by the frequency of the supply. They are of simple and robust construction and need little or no servicing as they have no commutator sliprings, brushes or governor. But few ships today have AC power for the main electrical supplies. Even if they had, it is unlikely that the frequency would be stabilised to limits satisfactory for an echo sounder timebase. A rotary converter is, therefore, used which can be considered as a motor driving an alternator. The motor is usually for 24, 110 or 220 volt DC. A similar form of centrifugal governor to that already mentioned is used to maintain constant speed in the motor section; then the alternator rotates at constant speed and its output frequency is stable.

Both the DC and AC timebase motors in use have running speeds, according to type, of between 1,000 and 3,000 rev/min. Such speeds are unsuitable for driving the pen of a recording echo sounder directly. In the case of a recorder giving a curved trace, where about 80 degrees of the total pen travel forms the scale, a speed of 3,000 rev/min would give a scale length of only about 3.5 m. Therefore, a system of gears is fitted, giving a suitable pen speed reduction for the scale required. There is usually provision for selection of different ratios so that the scale can be chosen to suit the particular depths required. Some recorders have four different gear ratios, typical basic depth scales being:

	1	2	3	4	
Depth scale	0–55	0–110	0–165	0–220	metres
Speed of pen	200	100	66.6	50	rev/min

Other methods of changing the scales than by gear changing are also used. For instance, the AC motors can be switched so that they run at half speed, thus making two basic scales available.

The term basic scale is used above because another method of extending a recorder scale is by phasing, as shown in Figure 16.

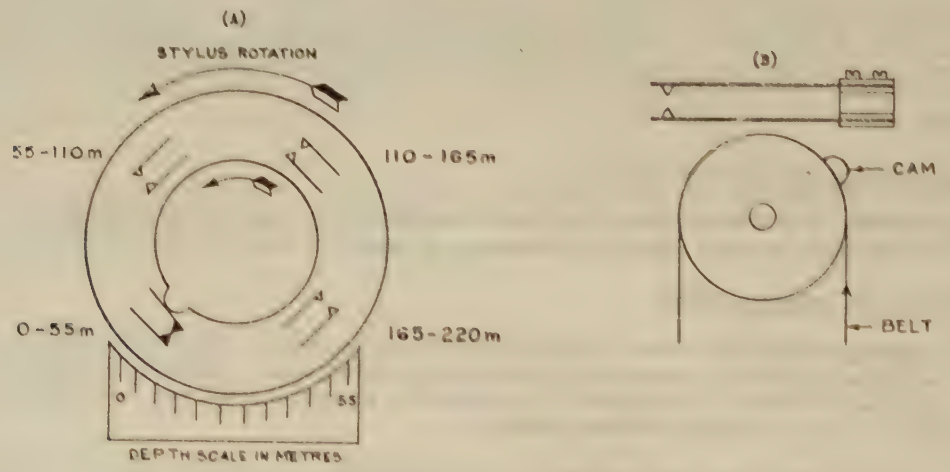


Figure 16 – (A) A method of depth extending the recorder scale by phasing.
(B) Transmission switch.

Phasing involves rotating the scale or switching to additional transmission contacts so that the zero (transmission point) occurs off the recording paper. On some recorders the scale may be rotated continuously, in which case a cam fitted near the zero point operates the transmission switch and the true depth reading can be read from the scale. This switch (Figure 16 B) usually consists of two contacts, both fitted to one end of a spring blade, whilst the other end of the blade is sandwiched between strips of insulating material. In other cases extra transmission contacts are located uniformly around the path of the stylus and operating cam. These contacts can be selected by a switch as required, but the phased scales need to be shown near the basic scale, and care is needed to avoid confusion when reading from them. In Figure 16, the switched circular system is used for clarity. From the table showing typical scales and numbers of revolutions of the pen, it can be seen that, for the scales shown, the optimum number of revolutions and transmissions is not used. This is because secondary or tertiary echoes can cause confusion in a system that is transmitting the optimum number of pulses and displaying all echoes. An example would be as follows: Using the recorder with a basic scale of 0–55 m we assume a sea-bed echo appearing at 50 m. The scale zero corresponds to time zero and the sea-bed echo to a time, 66.6 milliseconds later. As the stylus goes past the 55 m point at the end of the scale it, or another stylus, is about to pass the zero again, when another transmission is made. However, whilst the stylus is sweeping over the scale, the second echo from the previous transmission will appear at a time 133 milliseconds but showing falsely at a depth of 45 m (this phenomenon is described further in Chapter 3). Thus it is an advantage to keep the transmission rate at less than half the optimum.

Recorders have one or more stylus pens for marking the paper. For a one-pen system the number of revolutions made per minute by the pen is also the number of transmission that occur. Where n pens are used, the number of transmissions is n times the number of revolutions of the driving shaft or belt.

The interpretation of recorder charts is dependent on knowledge of the paper speed and its relation to the speed of the ship. The ideal arrangement for echo survey would be for the paper speed to be synchronized with the ship's movement over the sea bed, and when the ship stopped so would the paper.

This facility is not yet available, and on standard echo sounders the paper is driven by a reduction gearing or ratchet wheel. Typical paper speeds are between 2 and 25 mm per minute, which give some overlap of successive pen marking; as this speed is not related to the speed of the ship, the paper is marked in units of time. A small square or rectangular mark is usually arranged to appear before, or on, the transmission line every minute. This is very useful where a number of paper speeds are available, for the distance between the marks indicates the paper speed being used at a particular time.

(b) Cathode-ray-tube system

Cathode-ray-tubes are used for both vertical echo sounders and horizontal sonars; their advantage over the mechanical paper recorder is that a greatly magnified portion of the water column can be displayed. This is because the picture results from an electron beam striking the tube face and causing the phosphor to glow. The electron beam can be easily deflected at a very fast speed indeed, whereas a mechanical recorder cannot. Figure 17 A shows a block diagram of a cathode-ray-tube display.

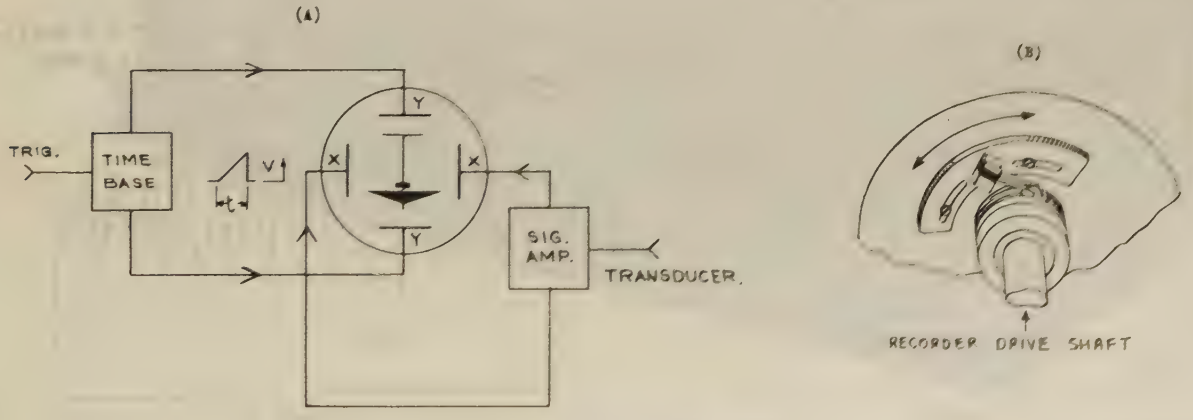


Figure 17 – (A) Block diagram of cathode-ray-tube timebase-display system.
(B) Switch contact for paper recorder–cathode ray tube slave.

The timebase generates a sawtooth wave synchronized by the trigger pulse; the sawtooth wave is a steadily increasing voltage which sharply returns to zero at the required time. When such a wave is applied to the metal plates Y, Y in the tube, the electron beam which is focussed on to its face will be deflected by the electrostatic field. This linear deflection forms the timebase. Signals from the transducer are amplified and applied to the plates X, X. Because they are still alternating either side of zero voltage, at the frequency at which they were transmitted, the spot will be deflected proportionally on the tube. Thus, for small voltage signals the spot does not travel as far as for large signals, and the smaller ones will, therefore, appear brighter. The phosphor is chosen so that the light decays quickly and so avoids trace-to-trace correlation which might be confusing.

There are three main ways in which the cathode-ray type displays are used:

(a) as a slave to a paper recorder;

(b) as a timebase and display for full seawater depth of full range of horizontal ranging;

(c) as a plan position indicator display for horizontal ranging (described in the sonar section).

The block diagram in Figure 17 A applies to the first two uses. In the simplest version of the slave system the trigger input comes from the paper recorder and is obtained from a switch contact, as shown in Figure 17 B. Thus any portion of the water column may be selected by moving the pointer until it corresponds with the required depth or range marking on the scale. The timebase for this system is made to run at a speed corresponding to a sound path length in water of around 10 m. This portion of the water column is shown across the full width of the cathode-ray-tube, which may vary from 7.5 cm to 15 cm.

Another slave system uses the transmission pulse as a time reference. Electronic circuits then provide time delays from this reference which can be made to correspond to any required depth or range. At this point, a further pulse is generated to start a timebase running at a sweep speed corresponding to 10 m, as above, giving a similar display. In this case the timebase is made to start at the time of transmission and finish at the maximum depth or range required. This is useful when no particular depth or range has to be monitored. When small echoes appear, it is usual to switch to a fast timebase (10 m). By using a variable delay unit, the fast timebase can be positioned over the small echoes, which can then be examined in detail.

2.2 Transmitter unit (Block Unit No. 2)

Trasmitters provide electrical power to the transducer when the transmission switch is closed. Although DC power was formerly used for this purpose, most echo sounders and horizontal echo rangers made for fish detection now have AC outputs. The following requirements must be met:

(a) constant power output

(b) constant frequency

(c) controlled pulse length

A typical pulse oscillogram is shown in Figure 18 A. This is an echo sounder pulse of 0.5 milliseconds duration with a frequency of 30 kHz. The period for1 cycle of a 30 kHz wave is 33.3 μ sec; thus 15 cycles are produced for the 0.5 millisecond pulse length.

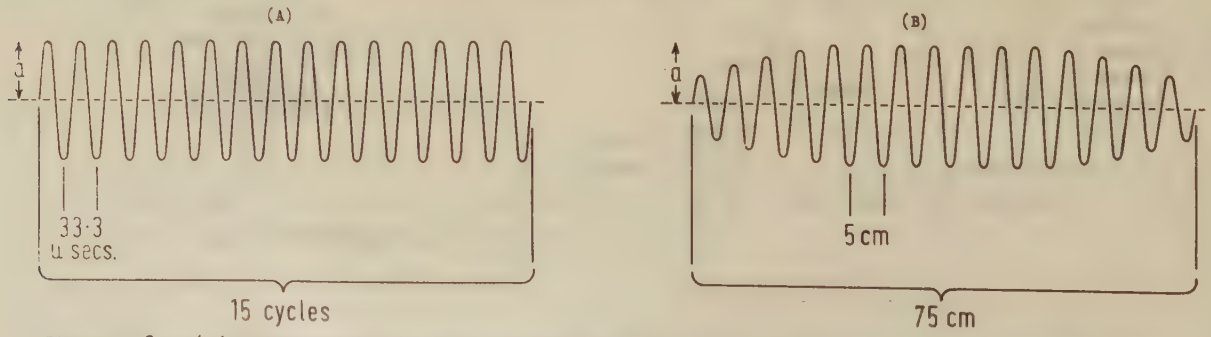


Figure 18 - (A) Vibrations of face of tranducer for a 0.5 millisecond, 30 kHz pulse.
(B) Resulting sound pulse.

Figure 19 is a block diagram of the trasmitter unit for an echo sounder or horizontal echo ranging system. In some systems the operation of the top three blocks, i.e. pulse length, oscillator and power amplifier, is carried out in one circuit. In this case, two vacuum tubes are connected in such a manner that they oscillate at the correct frequency for the duration of the pulse (pulse length τ) and at the peak to peak voltage V when the transmission switch is closed.

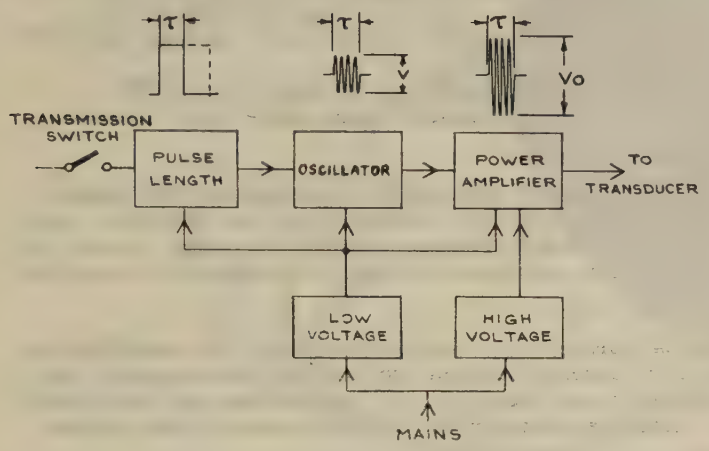


Figure 19 - Block diagram of transmitter unit for echo sounder or horizontal echo ranging sonar.

Pulse length can often be varied, either by switched positions, or continuously between typical limits of 0.3 to 2 milliseconds for echo sounding (1 to 25 milliseconds for horizontal echo ranging). A time constant of capacity and resistance determines it.

Frequency is fixed, or is within about 1 kHz of the specified operating frequency (transducer resonant frequency), and may be varied accordingly. A tuned circuit, consisting of an inductance and a capacitor, determines this frequency.

For constant power output, the supply voltages to the power amplifier tubes must remain at the correct level and the emission of the tubes must be up to standard. Tubes most commonly used for this stage are beam power tetrodes or pentodes of the type used in some television circuits.

Most of the present-day echo sounder have electrical peak power outputs of between ¼ and 1 kW. The tubes that supply this power can only do so in pulse form; they would quickly be destroyed if switched on continuously. The high DC voltage is usually 1kV of greater. It is very dangerous if touched.

2.3 Transducers (Block Unit No. 3)

The most commonly used transducers at present are magnetostrictive, an example being shown in Figure 20.

Figure 20 - Example of magnetostrictive type nickel transducer.

Such transducers are made from a material, usually nickel, which expands and contracts according to the direction of the magnetic field resulting from the applied electrical pulse. These dimensional changes cause pressure variations when the transducer is in water.

Figure 18 A represents the vibrations of the face of the transducer, transmitting at a frequency of 30 kHz at a pulse length of 0.5 millisecond. The resulting sound pulse is shown in Figure 18 B which shows that in the 0.5 millisecond period, 15 sine-waves, each having a wavelength of 5 cms would be produced, the length of the wave-train being 15 x 5 = 75 cms. Initially the amplitude of the transmitter pulse is low, due to the acoustic impedance, but it quickly builds up to maximum amplitude.

Efficiency of energy conversion, from electical to acoustic power, is between 25 and 50%. For 1kW electrical power input a typical acoustic level for a transducer measuring 9 cm x 15 cm is 110 db/μ bar/m.

The construction of magnetostrictive transducers is simple and robust. Laminations are stamped out of the nickel and treated so that they will be in poor electrical contact with one another. This avoids what is known as eddy current loss, caused by circulating currents induced in large volumes of metal. Holes stamped in the laminations carry the heavily insulated wire which couples the electrical energy into the transducer.

To obtain maximum efficiency, the nickel must be working at a suitable point on its magnetization curve. It is possible to arrange this by passing a DC current through the winding continuously, the pulse being superimposed. A more convenient method is to put slots in the laminations, so that small ceramic type permanent magnets may be inserted. These are found in the top and sides of many transducer units.

It is very important that the transducer should be coupled into the sea water medium efficiently, and for this reason paint and grease are always carefully removed from the outer surface. If a bubble stream crosses the face, this also decouples the transducer and power is not transferred well.

The magnetostrictive transducer is used from low frequencies up to about 100 kHz. An increasing number of echo sounders are, however, now being used at higher transmission frequencies, and for their transducers it is necessary to use other materials; those coming into regular use are barium titanate and lead zirconate titanate. The characteristic they exhibit is known as the "electrostrictive effect", which, in simplest terms, means a change of dimensions related to the applied electric field. Before use, the elements (consisting of material moulded into the required shape) must be polarized, and this is achieved by placing them in a strong electric field; electrodes, usually silver, are then applied to the necessary surfaces.

Because the surfaces cannot be in direct contact with sea water (this would short circuit the element and remove the electrode material), an assembly is required which will provide good electrical insulation and efficient acoustic coupling to the sea. If transducers are made from large blocks of the electrostrictive material, i.e. 7.5 cm^3 to 22.5 cm^3, they can be mounted on a pressure release material and encapsulated in epoxy resin, as illustrated in Figure 21.

More efficient forms of electrostrictive transducers are available which use small slices of the material sandwiched between critically dimensioned metal parts. Protection of the connections from sea water is by use of O-ring seals fitted to the metal parts.

For echo sounding at frequencies between 20 and 50 kHz, it is unlikely that the face of the transducer will be greater than 30 cm x 30 cm. The method of fitting the assembly into the ship varies, but in general two methods are favoured; they are limpet mounting or inserted mounting.

With limpet mounting the transducer assembly is completely external to the ship and only the wires pass through a gland in the hull. This allows a wider choice for positioning, and in some cases avoids the turbolence close to the hull. When fitting transducers to a ship, it is necessary to ensure that the face is at such an angle to the keel that when the vessel is in normal trim in a calm sea the transducer face is parallel with the sea surface. The limpet housing is usually shaped so that it presents least resistance to the water flow in the fore and aft direction.

Figure 21 - Example of barium titanate electrostrictive type transducer assembly.

An inserted mounting uses a steel housing which has walls as thick or thicker than the ship's plating at the point of insertion. Figure 22 shows typical installations.

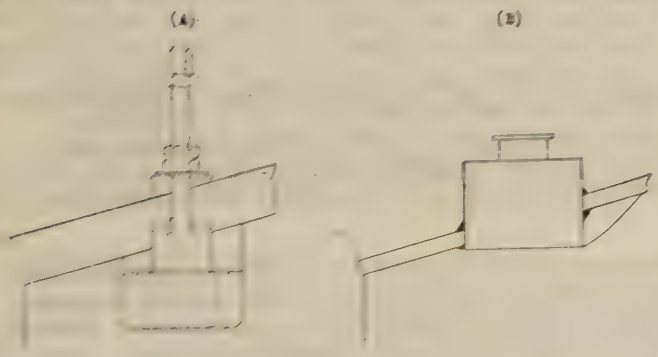


Figure 22 - Diagrammatic representation of transducer mounting.
(A) Limpet mounting
(B) Inserted mounting.

It is usual for the magnetostrictive transducer to be of rectangular shape rather than square. The half angle beamwidth to half power points of such a transducer is approximately $\sin \theta = 0.44\lambda$, where λ = wavelength in water and l = length of the transducer face. The logest axis is fitted fore and aft, thus giving the narrowest beam in this direction, this is typically 6 to 20 degrees. The beam width in the other direction is likely to be between 14 and 30 degrees.

2.4 Receiver amplifier (Block Unit No. 4)

Echo signals received by the transducer terminals may be very weak, sometimes only a few microvolts. Before they can be used for marking a paper record or deflecting the spot of a cathode-ray-tube, they must be increased in amplitude by perhaps 10^6 (120 db) or more: this is achieved by means of the receiver amplifier, shown diagrammatically in Figure 23.

For purposes of description the receiver may be split into three sections:

A. main amplifier

B. signal processing

C. paper-marking amplifier

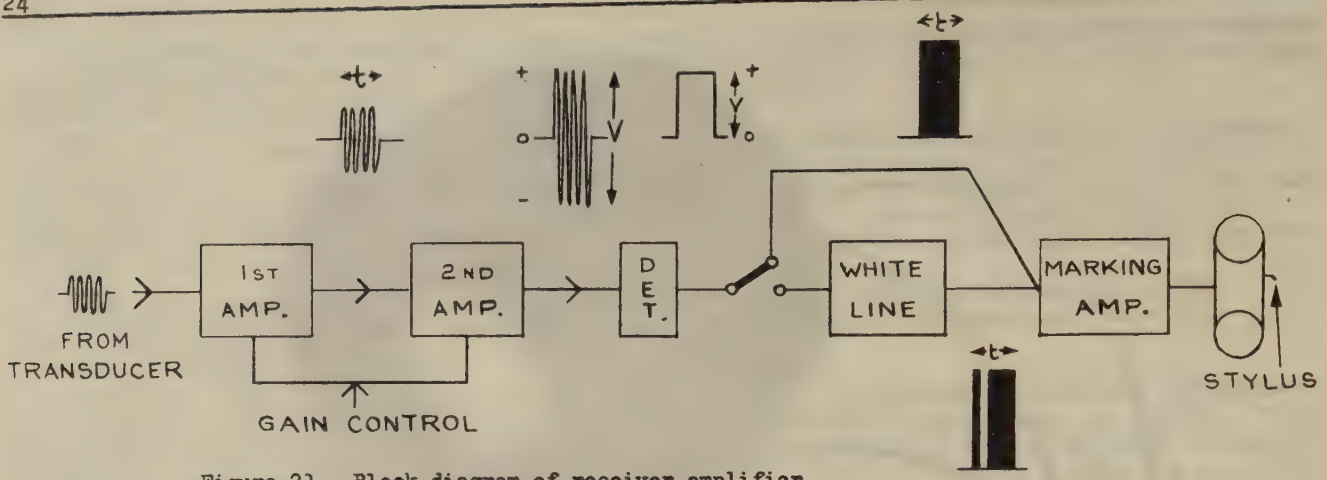


Figure 23 - Block diagram of receiver amplifier

A. The amplifier

The amplifiers are high gain tubes working in circuits tuned to the frequency of the transducer. Because one transducer is commonly used for both transmission and reception, care must be taken that the high voltages in the transmission pulse do not damage or overload the receiver input circuits. Neons which "strike" and become a low resistance when the voltage reaches a certain level are used for this purpose. Voltage sensitive resistors provide similar protection in some cases.

The amplifier must maintain a good signal-to-noise ratio. This means that during the amplification process the noise produced by the electronic circuits added to the noise received at the transducer terminals must not approach or exceed the echo signal level.

An important consideration in respect of noise is the receiver bandwidth. As the bandwidth increases so does the final noise voltage. However, if the received echo pulse signal is to be reproduced without serious distortion, a minimum bandwidth must be given which is related to the transmitted pulse length approximately by

$$\text{Bandwidth in Hz} = \frac{1}{2 \times \text{pulse length}}$$

Bandwidth is usually defined as the number of cycles (or Hz) between the points on a receiver voltage/frequency response curve where the voltage is 0.707 of the maximum, i.e. the 3 db points. Thus a typical receiver working at a nominal 38 kHz might have a gain of 10^6 at this frequency for a particular setting of the gain or sensitivity control. If the transmitted pulse length is 0.3 millisecond the approximate formula for bandwidth gives a figure of 1,600 Hz. This means that at 37.2 Hz and 38.8 Hz the gain would be 0.7×10^6.

The gain control is arranged to adjust the grid or cathode voltage of one or two of the amplifier tubes. It is continuously variable in most cases and placed in a prominent position on the equipment. Indeed in some modern sonar equipment a time-varied-gain system is adopted which automatically adjusts the amplitude of the received signals with range thus compensating for the transmission loss.

B. Signal processing

This is considered in its simplest forms as used in commercial production echo sounder.

(i) Initial suppression

When the transmission pulse passes into the receiver amplifier, it is usually reduced to a safe level by the methods previously mentioned. However, with the receiver at a high gain setting, reverberation may be considerable for the first few metres of water under the ship. To reduce this effect the transmission pulse causes a voltage to be developed across a capacitor in the input circuit, which reduces the gain of the first valve. The effect is arranged to die away quickly and is dependent upon the time constant of capacitance and resistance in this part of the circuit.

(ii) White or black line systems

These two systems are basically similar and the term "white line" will be used to describe them. When a sea-bed echo is displayed on a paper record and repeated trace-by-trace a distorted profile of the sea-bed appears. The distortion depends on a number of factors, including the sampling volume of the acoustic beam. If a large shoal of fish is close to the sea-bed it is likely to appear as a projecting feature of the sea-bed, when viewed on the paper record, and thus may not be recognised as a fish echo. By switching in an extra circuit to the receiver amplifier, shown in Figure 24, the actual sea-bed echo is reduced to a very fine line followed by a blank space and then the tail of the echo. The echo from the fish shoal, which previously merged with the sea-bed, can now be clearly seen sitting on the thin line (see, for example, Figures 36, 42 and 44 in Chapter 3).

This sort of processing is possible because of the differing amplitudes of the fish and sea-bed echoes. In cases where the fish echoes are very strong, some white line effects may also be observed on them (see, for example, Figure 41 B in Chapter 3).

C. Paper-marking amplifiers and styli

The details of such amplifiers will depend on whether wet or dry recording paper is used in the equipment. In some cases it is possible to change from one type to the other by changing the paper, the stylus and a switch. Dry paper requires a voltage of about 100 V or greater, whilst wet paper works well on 10 V or less. Furthermore, the dynamic range (the range of colours given by different voltages) is much greater for wet than for dry paper.

The dry paper has an electrically conducting back which is in contact with one of the marking amplifier output terminals. Connection from the other terminal is to the stylus pen, which is a fine steel wire running over the front surface of the paper. When a signal is received, the voltage on the stylus rises to such a value that breakdown of the front surface of the paper occurs, thus "burning" a mark. This type of paper usually has a grey background.

The wet paper is white; it must be sufficiently moist to have good sensitivity and give dense markings, but must not tear too easily in the paper drive, roller system. The paper is prepared by passing it through a solution of potassium iodide, water and starch. Very strict control is necessary in this process to ensure uniform marking later. Care is also needed in the storage of such paper rolls; they should lie on their sides, be turned regularly, kept in a cool place and stored for as short a period as possible before use. A DC voltage of 10 volts or less will produce electrolysis of the potassium iodide, with liberation of iodine, which combines with the starch to form a dense brown mark. Stylus pens used for such paper recorders are thicker than the dry paper types, usually having a highly polished tip. A minimum of two volts is needed for satisfactory marking.

A small power-amplifying type of vacuum tube is used for marking the paper. In the case of dry paper the output is taken from the plate circuit (high resistance) and for moist paper it is taken from the cathode (low resistance). In some cases it is taken via a transformer and rectifier system.

2.5 Sea-bed locked systems

All the systems described up to this point are known as transmission-locked. This is because the instant of transmission of the acoustic pulse is used as the time reference. Movement of the vessel with respect to the sea-bed is shown as a change of range on the recorder chart, and this movement may be quite rapid and result in a chart which is difficult to interpret. When considering fish echoes close to the sea-bed, e.g. within a distance of approximately 4 m from it, the normal recorder has a chart width of perhaps only 2 or 3 mm for this distance.

If the fish concentration is dense the "white line" circuits will show it clear of the sea-bed, but it may be that the fish are large ones spaced some distance apart, as is often the case for demersal fish, in which case they could be detected but lost in the "noise" recorded on the chart, due to loss of full trace-to-trace correlation.

For the detection of such fish concentrations, a system is required which will use the sea-bed as a reference. The problem is that the required fish echoes occur in time before the sea-bed signal for any given transmission period, i.e. the time between one transmission and the next. This means that the fish echoes occurring, for example, in the catching range of a trawl must be delayed in time, so that they occur in the processing circuit after the front edge of the sea-bed echo. It is beyond the scope of this chapter to describe such a system in detail, for the electronic circuits are complex, but both recording and cathode-ray-tube displays are manufactured with the sea-bed lock facility. In

both cases the sea-bed signal appears as a straight line at a fixed point on the display. Fish echoes up to about 8 m above the sea-bed are shown, often as individuals. The delay system can be a magnetic tape record which stores the signals for a given period. It also has the advantage that signals can be repeated many times, so that, in the case of the cathode-ray-tubes, instead of seeing the signals flash on once per second a continuous picture is presented.

3. HORIZONTAL ECHO RANGING SONAR

Most of the features of vertical echo sounders described in the preceding paragraphs apply equally well to the widely used, horizontal echo ranging equipment; in fact, if the transducer of a vertical echo sounder is turned 90° so that its acoustic pulses travel horizontally it could be termed a horizontal ranging sonar. However, as shown by the block diagram in Figure 24, this type of sonar equipment usually differs from echo sounders in the following main ways:

(a) It is possible to lower the transducer below the ship's keel and rotate it in azimuth (bearing control) (Block 6).

(b) There is an additional transducer control unit and bearing display.

(c) Transmitter power and pulse length are greater.

(d) The receiver amplifier has an additional feature of automatic gain control.

(e) An audio output is provided (Block 5).

The transducer is not fitted so that its beam is exactly horizontal. It is tilted downwards by about 5° so that reflections from the sea surface do not occur under normal conditions.

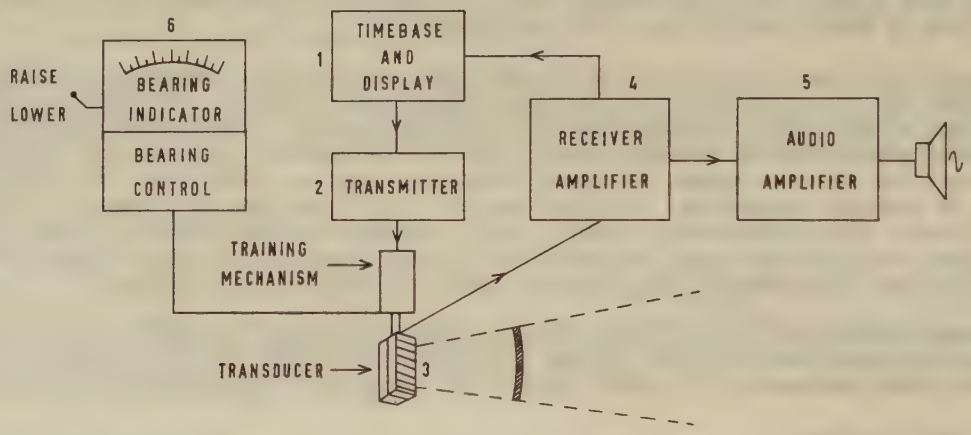


Figure 24 - Block diagram of horizontal echo-ranging sonar

Transmission frequencies used in this type of equipment range from 10 kHz to around 200 kHz, the lower frequencies being used for long-range detection because they suffer less attenuation in the sea. At the high frequencies range is short, but narrow beams from small transducers are possible and short pulses give good range resolution.

A typical horizontal echo ranging sonar working at 30 kHz might have a beamwidth of 10° x 10° with a switch to change the vertical part of the beam to 20°, so that a greater volume of sea can be searched. The active face of such a transducer would measure 25 cm x 25 cm.

3.1 Timebase and recording display

To be of practical use in fisheries, the sonar must be capable of detecting shoals of fish of a reasonable size at its maximum range. At a range of 1,500 m, it takes the sound pulse two seconds to travel from the ship, strike target and be reflected back. This means that the stylus travelling from zero to 1,500 m on the recorder paper will take 2 sec. If one stylus pen were being used on a recorder with a circular sweep, approximately three-quarters of the total 360° rotation of the pen rotation would be wasted, because during the time that the pen is off the paper the equipment is

inoperative. It would also mean that the time between successive transmission would be about 8 sec.

To avoid this wasted time, a number of pens are used so that as one leaves the paper at the maximum range another is passing zero. The number of transmissions and the sweep speed of the recorder can then be optimised. It is most unlikely that a secondary echo would be obtained from a fish shoal, so that the reasons given for not using optimum transmission and sweep rates on the echo sounder are, therefore, not valid for this type of equipment.

3.2 Automatic gain control

Initial suppression has been described as a simple form of automatic gain control for echo sounders. This system is also used for horizontal echo ranging sonar but a more elaborate control of overall sensitivity or gain is needed, because reverberation from quite long ranges can obscure fish echoes. To achieve this, the amplified signals, i.e. "noise" reverberation and echoes, are turned into a DC voltage whose amplitude depends on the number and amplitude of the signals. A proportion of the DC voltage is fed back to the amplifying tubes, so that the greater the "noise" or reverberation, the lower will the gain of the tubes become. Preset controls in the receiver allow the characteristics of the automatic gain control. This ensures that when a fish shoal echo appears, its amplitude is not reduced immediately by the DC control voltage; the gain stays constant until the echo ceases.

3.3 Control of transducer and indication of its bearing

Large volumes of sea can be searched by horizontal echo ranging sonar by rotating the transducer slowly from side to side as the ship steams ahead. The speed at which the transducer rotates is determined primarily by the longest range to be searched since time must be allowed for the sound pulse to travel from the transducer to the target and back again. In the case of the 1,500 m range quoted previously it is 2 sec. The transducer should not rotate through more than half its beamwidth in this time, or some signals may be lost.

An electric motor drives the transducer shaft via a gearbox, having a reduction of about 500 to 1, and it is also possible to rotate the transducer manually. The operator is able to "home" on to a shoal once it has been detected by means of the manual control. Manual training of the transducer by the operator rotating it from one side of the vessel to the other continuously would be very tedious and for this reason most echo ranging sonars have an automatic system of training, which can be left unattended. The transducer can be left to train from the extreme bearing on the port side of the ship, round to the extreme starboard bearing, or over some desired sector, in which case markers are placed on the azimuth bearing scale so that the desired sector is contained between them. Switches at the marker positions stop and reverse the training motor and this procedure can continue indefinitely.

The bearing scale, marked in degrees, is usually ± 150 degrees relative to the ship's head. A number of systems are used to convey the bearing information from the transducer to the bearing indicator, using electrical cables only. Synchronous links, or "synchros" as they are generally known, provide extremely accurate remote indication of shaft position or bearing. Potentiometres can be used with direct currents, but are not so satisfactory because of wear and sensitivity to voltage changes.

3.4 "Raise/lower" mechanism

Because the transducer has to "look" horizontally under the ship, it is mounted on a shaft which projects out by about 0.5 m. This shaft would be very easily damaged when dry docking or in other unfavourable circumstances, if it were left out of the hull. Another electric motor is, therefore, used to raise or lower the transducer when commanded by the control panel switch; an endless chain often provides the necessary drive from the motor, and switches fitted at the top and bottom of the travel distance stop the motor automatically.

3.5 Transmitter

The system shown in Figure 19 for the echo sounder applies for horizontal echo ranging sonar except that an additional power amplifier block is fitted between the existing one and the transducer. Thus Vo becomes greater, putting more power into the transducer. The electrical peak power level is usually between 1.25 and 5 kW. Pulses are variable between the limits of 1-25 milliseconds, so that the average power during the pulse is also greatly increased, compared with that of the standard echo sounder.

3.6 Audio output

The audio output enables the skilled operator to get more information from a particular target than the paper record can give. It is necessary to mix the received pulse with a signal near to its frequency; e.g. if we assume that the received pulse is at 50 kHz and that it is mixed with a signal of 51 kHz, the difference frequency is 1 kHz which is audible.

3.7 Plan position indicator

In the cathode-ray-tube systems described above for the echo sounder, the spot of light travelled in a straight line across the tube face, and signals caused sideways deflection of the spot. As shown diagrammatically in Figure 25, the plan position indicator (PPI) for the horizontal echo ranging equipment is quite different in appearance for, although the spot still travels in a line to provide the timebase, this line moves through a sector on the tube in synchronism with the transducer.

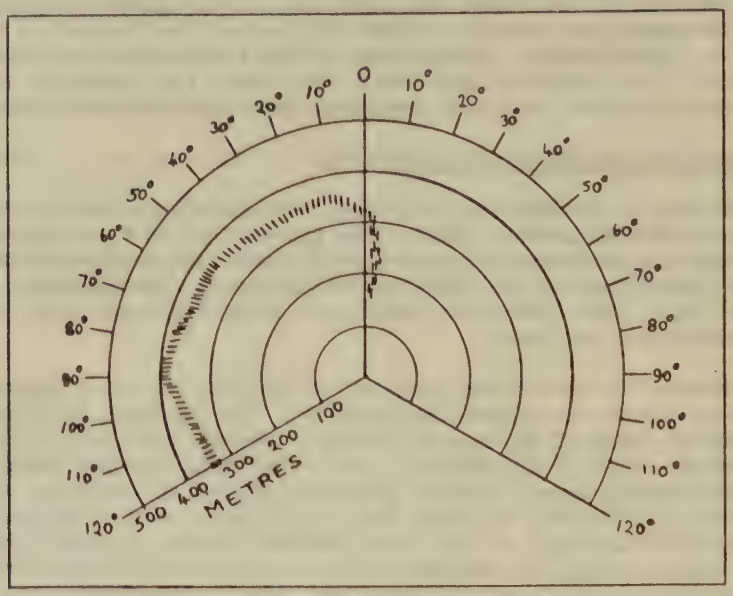


Figure 25 - Diagram of PPI display showing echo starting at 350 m range on 120° bearing and ending on 150 m range and 3° bearing.

Thus the bearing of a fish echo may be shown relative to the ship's head. In this system the echo signal causes an increase in intensity of the electron beam and brightens this point on the time-base line. The persistence of the tube phosphor is several seconds, so that echoes may be correlated from trace to trace. To obtain a PPI display, a type of cathode-ray-tube is used which has no deflector plates. The electron beam is formed and focussed in the same way, but the time base voltage is applied to coils which are rotated around the neck of the cathode-ray-tube and synchronized to the transducer bearing.

4. CALIBRATION OF SONAR SYSTEMS

There are two reasons why calibration is important for these systems. Firstly, to check that optimum system performance is obtained, and secondly, to enable the amplitude of signals received from fish and other sound scatterers to be related to known measurements.

The four main variables in echo sounder and sonar systems are:

(a) the transmitted power output;

(b) the transducer;

(c) sound transmission path (sea water);

(d) receiver amplifier sensitivity.

Typical specifications for the transmitter, transducer and receiver were discussed in previous sections. In the transmitter, it is necessary to measure the electrical pulse power delivered to the transducer to ensure that a constant acoustic output power level is maintained.

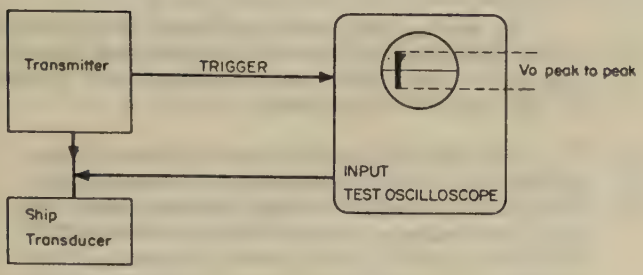


Figure 26 - Measurement of electrical power to transducer.

The sensitivity of the receiver can be checked by injecting a known voltage into it and checking the output for various settings of the gain control.

We are left with the transducer and sea water medium into which the acoustic pulses are transmitted. If the operating face of the transducer is clean, has no bubbles adhering to, or passing over it, we may assume that it is coupled into the sea efficiently. To obtain detailed characteristics of a transducer, special equipment is needed. Also, the measurements often need to be taken both in air and in water which is not practical once the transducer is fitted to a ship.

In general, methods of calibration are used which avoid precise knowledge of the the ship's transducer characteristics.

4.1 Calibration using a known test transducer

This method involves the measurement of the sound source level of the transmitting system and the overall sensitivity of the receiving system. Transmission source level is dependent on the electrical power input to the transducer, the efficiency of conversion of electrical to acoustic energy, and the directivity of the transducer. Receiving system sensitivity depends on the efficiency of conversion of acoustic energy (received echo) to electrical energy (signal to receiving amplifier) by the transducer, and the gain control setting. A number of instruments are required for these measurements as below:

(a) Calibrated test transducer or hydrophone. It is important to obtain the calibration for both reception and transmission.

(b) Oscilloscope with calibrated time and amplitude scales.

(c) A signal generator, preferably having both pulse and continuous wave outputs. This must cover the frequency of the echo sounder of sonar system under test. It should have a calibrated output voltage or an attenuator calibrated in db relative to 1 volt at a known impedance.

When this type of measurement is being carried out, the ship should not be close to a quay or in water shallower than 10–15 m. It is important to pick an area where there are no fish or dense concentrations of plankton as the presence of these would affect calibration. All the electronic equipment, test gear and echo sounder should be run for 30 min before any measurements are carried out. By this time any tendency to change characteristics due to warming up should have disappeared.

4.2 Echo sounder calibration

Usually, the test transducer or hydrophone cannot be rigidly fixed beneath the ship's transducer which is to be calibrated, so it is necessary to ensure that it is placed, and stays, in the centre of the echo sounder beam.

The stransducers should be kept 3 m or more apart and for this purpose a special rig is needed for lowering under the ship to get the test transducer in position. A framework supported by wires or ropes from each side of the ship carries the transducer on top and is weighted on the underside.

The test transducer cable is connected to the amplifier input of the oscilloscope. A connection from the echo sounder transmitter triggering circuit should be connected wo the 'EXTERNAL SYNC' or

or 'TRIGGER' input of the oscilloscope. As the distance between the transducers is small, the 'SWEEP SPEED' can be set at 0.25 or 0.5 milliseconds per cm of graticule. For a transducer spacing of 3 m the receiver signal would appear 4 cm from the transmitted signal with an oscilloscope sweep speed of 0.5 milliseconds/cm. The amplitude may be adjusted by varying the oscilloscope calibrated amplifier control.

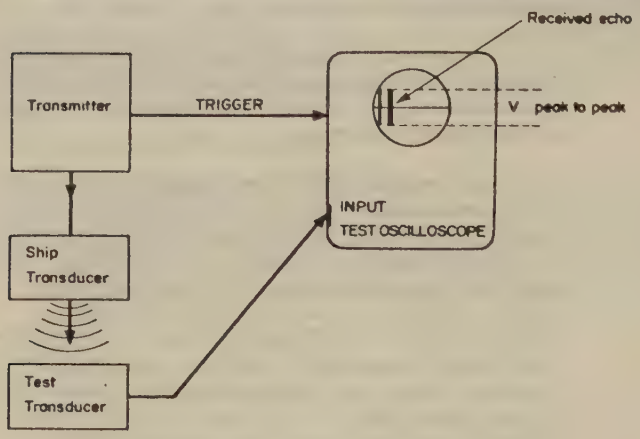


Figure 27 - Measurement of received signal V to obtain V_R.

By moving the test transducer horizontally, it is possible to observe the received signal change in amplitude. Maximum amplitude occurs in the centre of the beam.

The exact distance apart of the transducers can now be determined by measuring the pulse propagation time between them. As the oscilloscope trace is being started by the transmitter, it is merely necessary to measure the horizontal scale in milliseconds between the transmitted and received pulses. Assuming that the time measured was 2 milliseconds and the velocity of sound in the sea area of the test = 1500 m/sec

$$\text{distance} = Vt = \times 1500 \times 2 \times 10^{-3} = 3 \text{ m}$$

Velocity must be measured either directly by means of a velocimetre, or by temperature and salinity measurements, which are referred to tables.

When the above procedure has been followed, it is possible to start measuring the sound source level referred to a point 1 m from the transmitting transducer face.

This is given by the expression

$$S_L = V_R - S_{Rt} + 20 \log_{10} r$$

where S_L is the source level in db/μbar/m,

S_{Rt} is the sensitivity of the test transducer as a receiver in db/volt/μbar,

r is the distance in metres between the two transducers,

V_R is the output developed across the receiving transducer in db/volt.

Example

To obtain V_R the peak to peak voltage is measured off the vertical marking of the oscilloscope graticule. It is divided by two and multiplied by 0.707 to give the Root Mean Square (R.M.S.) voltage. If the peak to peak reading were 8.6 volts,

$$V_R = 20 \log_{10} \left(\frac{8.6}{2} \times 0.707\right),$$

$$20 \log_{10} (4.3 \times 0.707) = \underline{5.66 \text{ db/volt}}.$$

If r = 3 m $\quad 20 \log_{10} 3 = 0.4771$

$$\underline{\underline{9.5420}}.$$

A typical figure for S_R would be -98 db/volt/μbar;

S_L then = 5.66 - (-98) + 9.54 = 113.2 db/μbar/m.

By using this system of measurement, the first three variables listed at the beginning of this section have been taken into account for the sound wave transmission process.

The receiving system is calibrated by a reciprocal process. Sensitivity of the whole receiving system is given by:

$S_R = V_s + S_{tt} - 20 \log r$ db/μbar ref. to standard output voltage,

where V_s = R.M.S. output from the signal generator in db/volt

+ receiver amplifier gain setting (db),

S_{tt} = sensitivity of test transducer as a transmitter in db/μbar/volt/m,

r = distance in metres between the transducers.

For this measurement, the cable from the test transducer is connected to a signal generator which must be tuned to the frequency of the system. The echo sounder transmitter is switched off because the signal generator and test transducer now form the transmission system and the ship's transducer only receives signals.

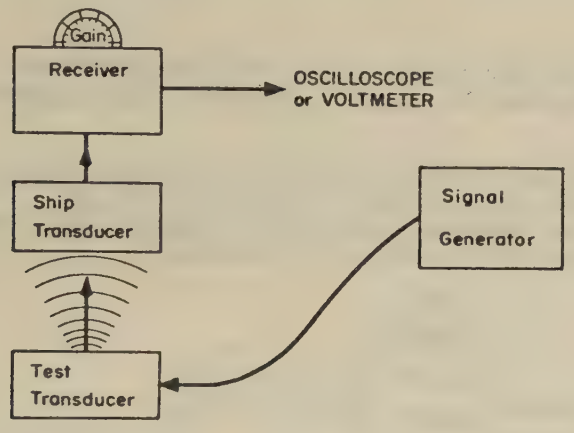


Figure 28 - Calibration arrangement for receiver.

It is difficult to calibrate an echo sounder receiving system using a paper recorder as the output indicator. Minimum Recordable Signal on the paper is a useful reference but is not precise enough to be used as a basis for calibration.

This difficulty is overcome by connecting either an oscilloscope or high impedance voltmetre to the receiver output across the terminals of the recording stylus. A load resistance is also fitted in place of the stylus, the value is not very critical being typically 2 to 5 kilo-ohms for a moist paper recorder and 20 to 50 kilo-ohms for a dry paper type. Of course, the same value should always be used for a particular equipment. An output voltage must now be chosen which will be the reference for calibration, this would be between 4 to 10 volts in a moist paper system and 70-100 volts with a dry paper.

Before proceeding with the full receiver system calibration it is often better to calibrate the receiver gain control with no transducer connected. This is because at higher gain settings water noise may make the readings unsteady. If this is to be done the transducer must be replaced by a 'dummy' load which is its electrical equivalent.

The signal generators made for echo sounder work have very low impedance outputs and can be used connected in series with the transducer. One particularly suitable generator has two outputs, one of 0.1 ohms for series connection. The other is a loop through which one of the transducer leads is passed. This gives an effective series resistance of 0.001 ohms, which is quite an insignificant increase in transducer circuit resistance. If a signal generator, as described above, is connected in circuit with the dummy load and tuned to the echo sounder frequency, an output should be seen on the oscilloscope or voltmetre. Pulse on oscilloscope, C.W. on voltmetre or scope. Assuming the receiver gain control is turned to maximum, a low output voltage will be needed from the signal generator to produce the reference voltage. When this has been noted, the gain control is turned down one division and the increase in voltage or db of the generator output to obtain the reference voltage is noted.

For example, if the signal generator output is calibrated in voltage and a 50 millivolt (0.050 volts) output from it is needed to produce the receiver standard output voltage on gain control division 2, this is referred to the signal generator voltage for maximum gain - say division 10. Assuming that an input to the receiver of 5 microvolts (0.000005) was needed at gain division 10, gain at division 2 would be $= 20 \log_{10} \frac{50 \times 10^{-3}}{5 \times 10^{-6}} = 20 \log_{10} 10^4 = -80$db with respect to maximum gain. After the above procedure is completed the full calibration can be continued. Remove the ship's transducer dummy load if this was used.

The signal generator is connected to the test transducer suspended below the ship, and its output voltage level adjusted so that the standard reference voltage is obtained from the receiver. For example, we will assume that the receiver gain control is still at division 2 as above.

V_s = signal generator output in db/1 volt + receiver gain.

Assuming the signal generator voltage to be 100 millivolts, i.e.

$$20 \log_{10} \frac{1}{10^{-1}} = -20 \text{ db/1 volt.}$$

$V_s = -20 + (-80) = -100$ db/1 volt,

S_{tt} = 30 db/μbar/volt/m assumed,

20 log r = 9.54 if the test transducer is at the same distance as used for the source level calibration.

$S_R = -100 + 30 - 9.54 = -79.54$.

If a cathode-ray-tube display is provided as part of the echo sounder system, this should also be calibrated and it will be of greater operational value than the receiver calibration for a recorder system.

Two methods of connecting the CRT display into the echo sounder or sonar system are commonly used. The calibration details will depend on the method of connection. In the first case, the amplifier for the CRT having its own gain control is connected to the receiver output. Thus, the receiver gain control and the CRT gain control both affect the gain of the display.

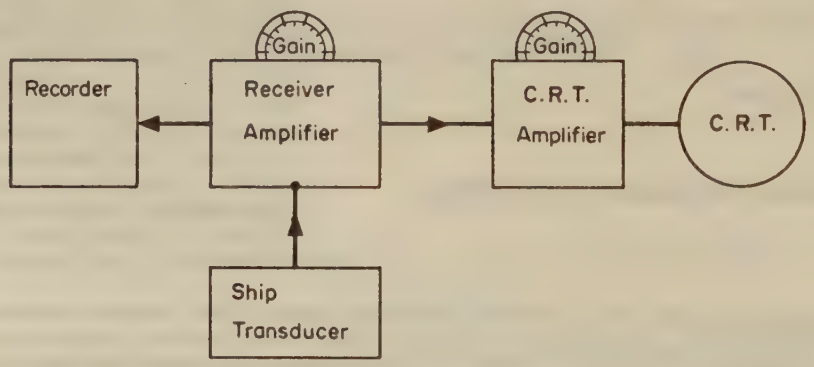


Figure 29 - Gain control for series amplifier system

For the second case, the CRT display has a complete receiver amplifier which takes signals from the common transducer. Thus, the gain controls for recorder and CRT will be independent and a separate calibration is made for each part of the system.

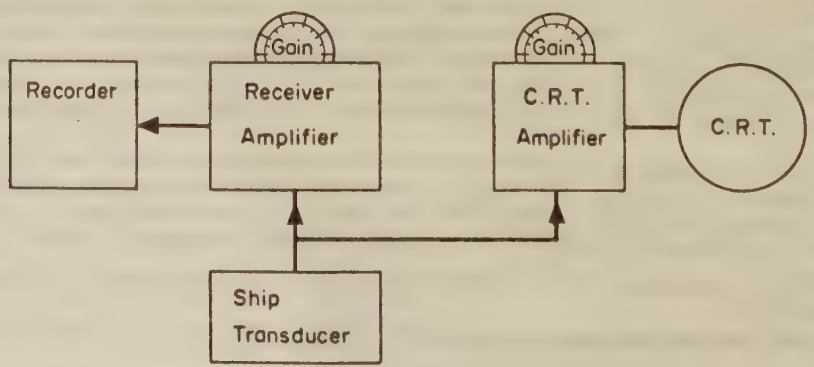


Figure 30 - Independent gain control system.

Sonar systems

The same method can be used for sonar systems, but of course the test transducer in this case must be positioned with its face parallel to the ship-fitted transducer at an appropriate distance. Vertical positioning must be finalized by raising and lowering the test transducer, whilst in the horizontal plane this is done by training the ship's transducer. Maximum signal amplitude on the oscilloscope or receiver output voltmetre is again the best criterion.

CHAPTER 3

CHARACTERISTICS OF ECHO RECORDS

G. Saetersdal and G. Vestnes

As shown in Chapter 2, the information produced by ech sounders and horizontal echo ranging equipment is usually presented in a visual or audible form. The most common form of presentation is a two-dimensional paper recording and this chapter deals mainly with this type of echo record.

The uses to which echo sounders and echo ranging equipment are put in fishing and fisheries research are to determine the depth of water, the nature of the sea bed and the kinds, sizes and amounts of fish present. The analysis of the echo records, their classification and interpretation is a vital part of this work. The nature of the echo records is determined not only by the types of targets, but also by a number of characteristics of the acoustic instruments themselves and by the operating conditions. The maximum amount of information can usually be obtained from echo records only after long periods of personal experience. In this chapter, however, an attempt is made to explain the basic principles connected with the interpretation of echo records and by demonstrating examples of various characteristic types of echo records.

1. ECHO SOUNDER RECORDS

1.1 General characteristics of echo records

In the ordinary vertical echo sounder, the sound beam can be likened to a searchlight, always pointing from the transducer in the bottom of the ship towards the sea-bed, as shown in Figure 31. But unlike a continuous searchlight beam, the sound beam is pulsed and the water column is "searched" on each occasion when the sound-pulse is emitted from the transducer. The shape of the beam, the length of the sound pulse and the frequency of the sound are all factors of considerable importance in determining the type of echo record produced.

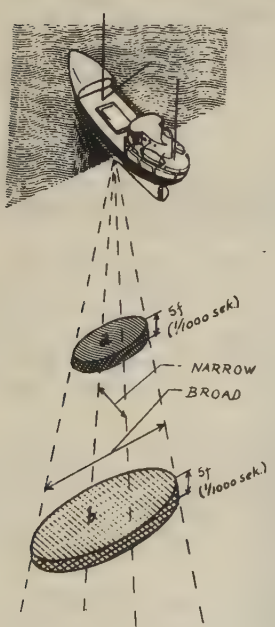


Figure 31 – The echo sounder pulse and the shape of the sound beam.

As described in Chapter 2, the transmission frequency is a fixed characteristic of the instrument and cannot be varied. The beam shape is sometimes variable if several transducers or multiple-angle transducers are used. The pulse-length can also be varied in more advanced types of instruments. Other controls of echo sounders which affect the echo records, and therefore are important for their understanding, are the sensitivity, the transmitting power, the depth range selector, the paper speed, the type of recording paper and the "white-line" effect. The influence of these controls and characteristics on the various types of echo records will be discussed in detail in later sections; here attention will be confined to a few points of general interest.

The shape of the sound beam is in many echo sounders narrower in the fore and aft direction than abeam. A narrower fore and aft beam will give a better horizontal resolution of the echo records while a wider width of the sound beam will ensure better coverage. As shown in Chapter 1, the sound beam is not cylindrical, but conical and the sound energy is distributed over a wider area as depth increases, as shown in Figure 31. For example, at a depth of 200 m, the area of the sound cone is about four times its size at 100 m. This is the main reason why echoes from targets near to the transducer are stronger than from those at greater depths. As shown in Chapter 2, more advanced instruments have an automatic built-in sensitivity control (time-varied gain – TVG) which compensates for the reduction of the sound field intensity with depth so that the effects on the received echoes of distance from the transducer are eliminated.

One effect of a change of the speed at which the recording paper passes through the recorder is to change the relative dimensions of the echo records. The horizontal scale of the echo record depends on the paper speed as well as on the speed of the vessel. The effect of a change of either of these factors is illustrated in Figure 32.

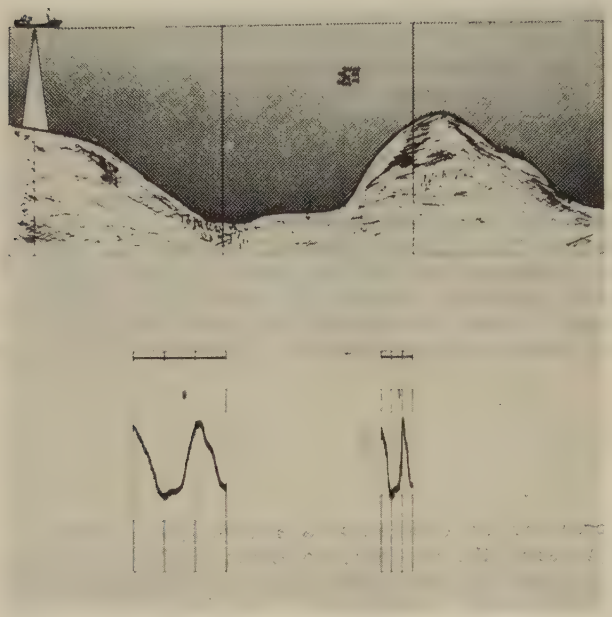


Figure 32 - The relative dimensions of echo sounder records at different paper speeds.

In the upper part of this figure, the topography of the bottom is drawn in the same horizontal and vertical scales and the two echo recordings shown below were made with paper speeds of 15 mm/min and 5 mm/min respectively. A similar change would have been produced at a constant paper speed by a change of vessel speed from 5 knots to 15 knots. One should note that in ordinary paper-recorders the horizontal and vertical distances are shown at widely different scales. At normal cruising speed, the vertical scale will be twenty times or more greater than the horizontal one and this will, of course, result in a corresponding distortion of the relative dimensions of, for instance, fish schools which are recorded. Thus, the characteristic traces of fish schools often described as "plumes" and "comets" only exist on echo diagrams and their shape will depend on the amount of distortion of the horizontal and vertical dimensions which accordingly will vary with the paper speed, the pen speed and the speed of the vessel. Such characteristic shapes of schools, often used for purposes of identification, are thus not always directly comparable between vessels and different kinds of equipment.

Most echo sounders have a constant transmitting power, but in a few types the power can be varied usually in two steps, full and $\frac{1}{10}$ effect. In shallow (10-50 m) and narrow waters the reduced transmitting power is an advantage because double reflex echoes and horizontal echoes are avoided or reduced. At greater depths the full power should always be applied.

1.2 Records of sea-bed echoes

Besides depth, the echo sounder may give information on a number of characteristics of the sea-bed itself. The most important are whether it is smooth or rough, soft or hard and its slope. Figure 33 demonstrates several of these characteristics.

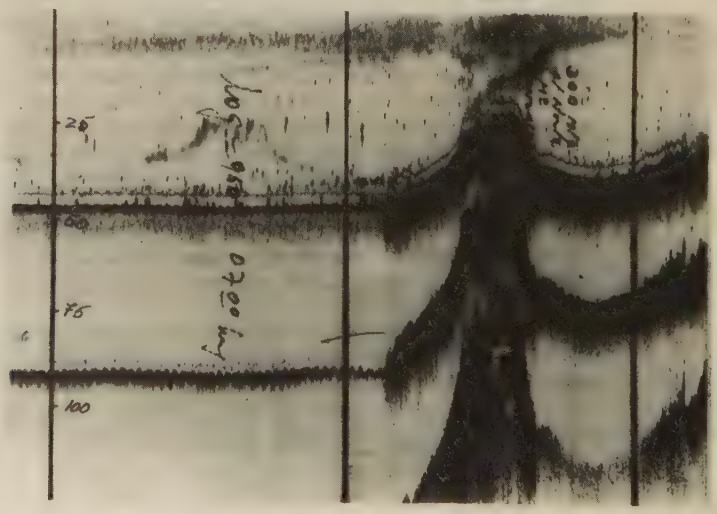


Figure 33 - Echo sounder record of smooth soft bottom, and uneven hard bottom. (Note also double and triple bottom echoes)

On the left of this echo diagram the vessel passed over level, smooth ground, which suddenly changed to rough and uneven. It can also be deduced from the recording that the smooth, even ground was soft and the uneven ground was hard, probably rocky. The difference in width of the two types of traces indicates this. The soft ground echo was weaker and, therefore, produced a narrower trace than the stronger echo reflected from the hard ground. This is due to the differences in their reflectivity so that the narrower trace comes from an effectively narrower beam. The width of the trace will, of course, also vary with the depth and the sensitivity used, but with some experience and training the operator will be able to judge the character of the sea-bed from the echo record.

Layers of sea-bed deposits may be recorded with certain types of echo sounders. Figure 34 shows an example from a study where a search for deposits of soft mud was used to locate habitats for deep-water shrimp.

Figure 34 - Echo sounder record of layers of different kinds of bottom deposits in a Norwegian fjord (from Rollefsen, 1935).

In shallow waters not only one but several echoes may be obtained from the sea-bed. This is because the sound, after having been reflected from the sea-bed back to the ship is reflected down again by the sea surface and thus produces a second sea-bed echo. A whole series of such echoes may be recorded. Figure 33 shows a second and a third echo.

The gradient of the bottom is easily judged from the echo diagram. Figure 35 shows a record of a steeply rising bottom where the depth range was changed from 300–425 m through 200–325 m to 100–225 m to cover the bottom variation. The gradient presented on the echo diagram depends, of course, on the speed of the vessel, the pen speed and the paper speed used. It should also be noted that the recorded depth over a steeply sloping bottom will underestimate the true depth, and the gradient measured from the echo record will also tend to differ from the true gradient.

When using a sensitive echo sounder in depth of water beyond the depth scale set on the recorder, the so-called "ghost bottom" may be recorded. This is the true sea-bed echo being recorded at an incorrect scale. When the sea-bed is beyond the set scale the pen returns to the zero position before the sea-bed echo returns, and a new transmission is made before the echo is recorded. Figure 36 shows an example of a "ghost bottom". It is characteristic that the echo passes the zero line.

In this example the trace disappears at very shallow depths. This is caused by the initial suppression of the echo sounder in the range 0–10 or 20 m and it demonstrates that the echoes from the "ghost bottom" were relatively weak. Another demonstration of the weaker echo from a "ghost bottom" as compared to that from a true, shallow sea-bed recording is that the "white-line" effect will usually not occur in the "ghost bottom" trace. The "ghost bottom" recording has given rise to many reports on new, hitherto unknown, shallow banks and great fish concentrations which have mysteriously disappeared on further investigation. An experienced operator can, however, easily recognise "ghost bottom" traces.

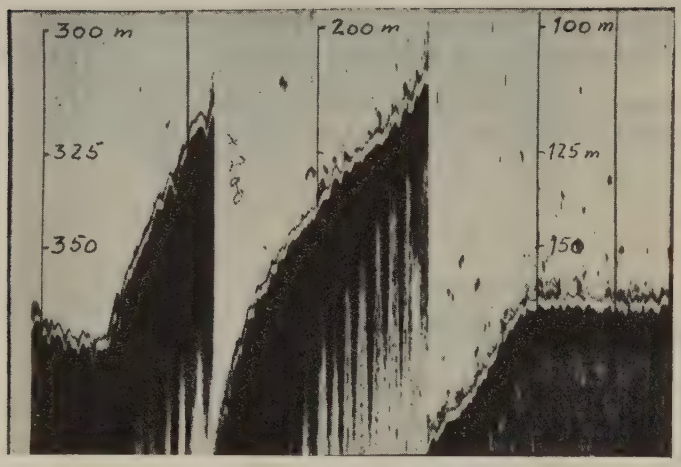


Figure 35 - Echo sounder record of steeply rising bottom with shift of depth ranges in order to cover bottom variations.

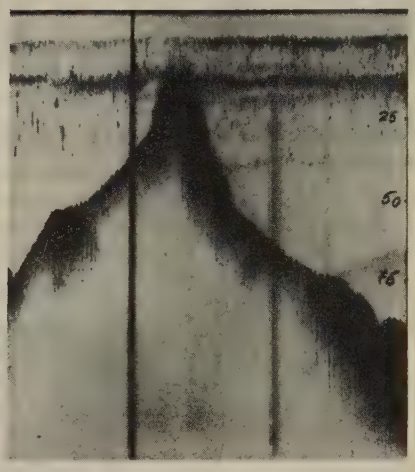


Figure 36 - Echo sounder record of "ghost bottom".

1.3 Records of fish echoes off the sea-bed

Echo sounders have been used for fish detection since the mid 1930's. Figure 37 shows one of the first echo records of fish, taken in 1935, of schools of spawning cod on the Lofoten Banks in North Norway.

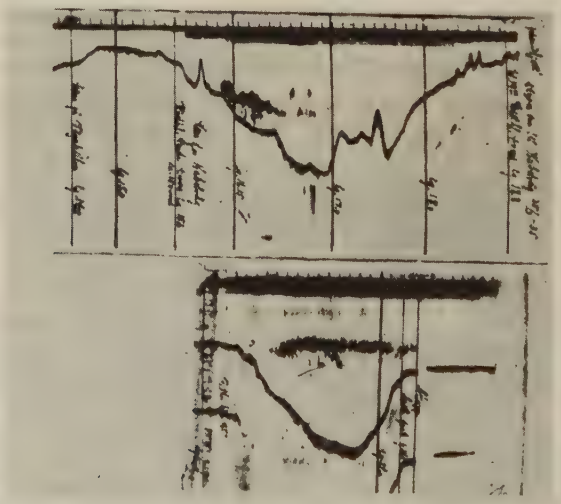


Figure 37 - One of the first fish recordings by echo sounder. Schools of cod on the Lofoten Banks in North Norway (Sund, 1935).

The types of echo sounders available when this record was taken only recorded heavy concentrations of fish in relatively shallow water. Since then, the sensitivity of echo sounding has increased greatly and a good modern fish detection echo sounder can record a single fish at a depth of several hundred metres. However, high sensitivity is not the only factor governing the effectiveness of the echo sounder for fish detection and for determining their kind, size and abundance. In addition to high sensitivity we need as much detailed information as possible, and the degree of detail that can be obtained depends to a great extent on the power of resolution of the instrument.

1.3.1 Single fish records (resolution)

Fish records may show each individual specimen separately, or the echoes from two or more fish may overlap or join up to form a multiple echo. It is of interest to study the conditions for the recording of individual specimens separately. In the vertical direction, this will be related to the pulse-length of the transmitted sound. As shown in Chapter 1, if the vertical distance between two fish is less than about half the pulse-length, their echoes will overlap. A simplified diagram, illustrating this is shown in Figure 38. (Because of inertia in the transducer, and the other components of the echo sounder, the critical distance, is in fact somewhat greater than half the pulse-length).

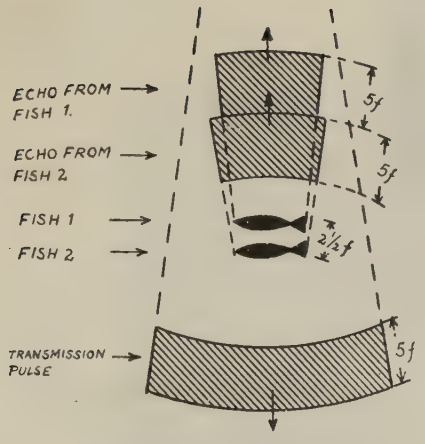


Figure 38 - Simplified diagram of echo from two fish separated by half the length of the sound pulse. The pulse has just passed the fish, and the echoes are on their way.

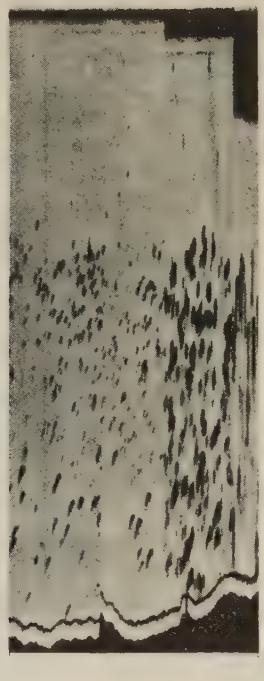


Figure 39 - Echo sounder record of single fish using three different pulse-lengths; 1 msec (left hand trace) 3 msec (middle trace) and 12 msec (right hand trace).

The duration of the sound emitted at every transmission in ordinary echo sounders is of the order of 1 or 2 milliseconds. With a duration of 1 millisecond the corresponding length of the sound pulse is 1.5 m. Two milliseconds will give a sound pulse of 3 m. Figure 39 shows a fish record where the pulse-length was varied from 1 millisecond to 3 milliseconds and finally 12 milliseconds.

The higher power of resolution at the lowest pulse-length shown on the left-hand side of this echo record is clearly evident. In echo sounders where the pulse-length can be varied it is recommended to keep this control at about 1 millisecond. The longer pulse will, however, in most instruments increase the transmitted energy and it is recommended for use in sounding at great depths and when high resolution is not needed.

The beam angle is of great significance for the horizontal resolution, the narrower the beam, the greater the resolution.

In some recent types of echo sounders, designed for research purposes, very short pulse-lengths have been used along with relatively high transmission frequencies (100-200 kc/s), and narrow beams, in attempts to resolve individual fish in dense concentrations. Figure 40 shows a herring school recorded on a 30 kc/s echo sounder with a pulse-length of 0.5 milliseconds and wide beam (lower trace) and on a 100 kc/s echo sounder with a pulse-length of 0.08 milliseconds and narrow beam (upper trace). The vertical resolution is evidently much greater in the latter case.

Figure 40 - Comparison of echo sounder records of a herring school obtained with an echo sounder using 100 kc/s sound frequency and 0.08 msec pulse length (above) and correspondingly 30 kc/s and 0.5 msec (below). The higher resolution of the upper record is clearly evident. (Record of Fisheries Laboratory, Lowestoft)

1.3.2 Characteristics of single fish records

The recordings of single fish will vary greatly in appearance between different types of echo sounders and different operating conditions. With the vessel lying stationary single fish remaining in the sound beam will be recorded as continuous line traces, as shown in Figure 41 A. At slow speeds the lines shorten and become curved (Figure 41 B) and at high speeds they appear as dots or points (Figure 41 C). The reason for this is, of course, that the number of echoes obtained from each individual decreases as its speed of travel through the sound beam. The beam angle in the ship's direction of travel will also influence the appearance of the single fish traces: the wider the beam, the longer the individual traces.

Figure 41 A - Echo sounder traces of single fish when vessel is stationary.

Figure 41 B - Single fish traces at slow speed, note inverted v-shape.

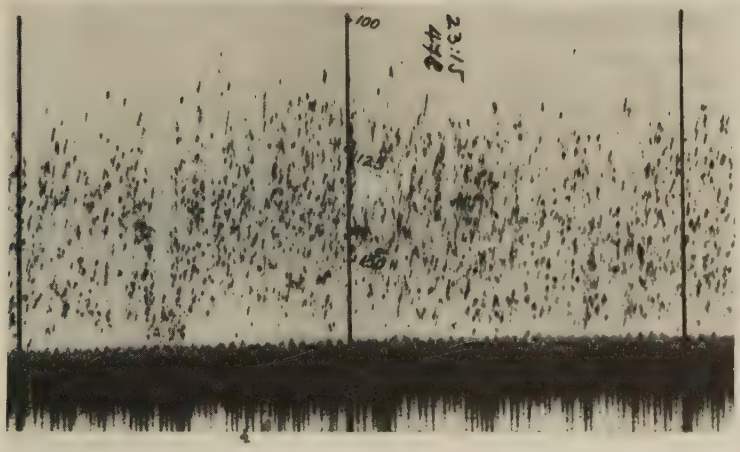


Figure 41 C - Single fish traces at full speed of vessel.

The curved line or inverted v-shaped traces appearing in recordings at relatively low speed (or with a wide-angle transducer even at high speed) are typical of single-fish traces. They are caused by the fact that the distance between the fish and the transducer is greater when the fish is near the edge of the beam than when it is directly under the ship. Figure 42 shows this. When the ship is pitching or rolling this characteristic shape may be difficult to detect.

Although it is desirable for quantitative evaluations to use a narrow beam, it is usually necessary for purposes of identifying the kind of fish being recorded that a well-defined trace of individual fish is produced, i.e. a succession of echoes from the same individual which takes the form of a compact continuous trace. The beam angle should, therefore, be related to the sounding rate and the paper speed in such a way that several echoes are obtained from individual fish at normal cruising speeds.

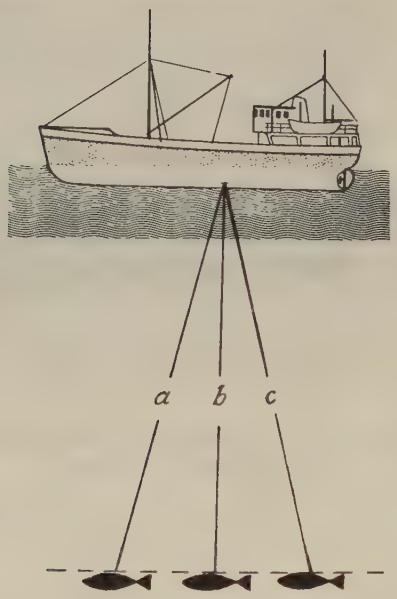


Figure 42 - One fish in three different positions during passage of the sound beam. The oblique distances a and c are greater than the vertical distance b.

(A) (B)

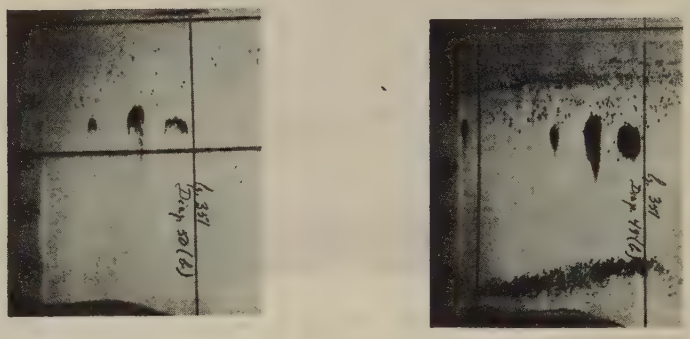


Figure 43 - Comparison of echo sounder records of the same targets without (A) and with (B) time-varied gain. Note that the fish layer (probably mackerel) at 200 m depth is completely missed by the top record.

As shown in Chapter 1, the intensity of the signal from a target of a given target strength decreases as the 4th power of its range from the transducer. Therefore, it is necessary to adjust the gain on the amplifier to maintain the recorded signal strength from targets at increasing ranges at the same level. As shown in Chapter 2, some types of echo sounders automatically compensate for the decrease in signal strength with depth by the introduction of a time-varied-gain system. An example of an echo record taken with such a system is shown in Figure 43.

The use of time-varied-gain is of importance when making measurements of target strength of individual fish at sea, and in discriminating between different types and sizes of fish throughout the depth range. If time-varied-gain equipment is not available, it is often advantageous to run two echo sounders (preferably of different transmission frequencies) simultaneously, one to cover the upper water layers, at a relatively low gain and the other to cover the deeper layers, at a relatively high gain. Such a procedure is often facilitated by the fact that fish concentrations giving rise to single echoes are often distributed within a certain depth interval, such as shown by the record of large spawning cod from the Lofoten area reproduced in the upper trace in Figure 46 A.

1.3.3 Records of fish in layers and schools

When the fish density exceeds the limit of the power of resolution of the echo sounder used, the record takes the form of a multiple echo trace, which may appear as a layer or as a distinct, solid trace. There is, of course, a continuous transition from dispersed layers or bands, where the echoes from a large number of single individuals can still be identified, to dense layers and schools. Figure 44 A shows some examples of different types of layers and distinct schools of small herring, while Figure 44 B shows the same for adult herring. One should note that the paper recorders do not, per se, give adequate information on the density of fish in such layers or schools.

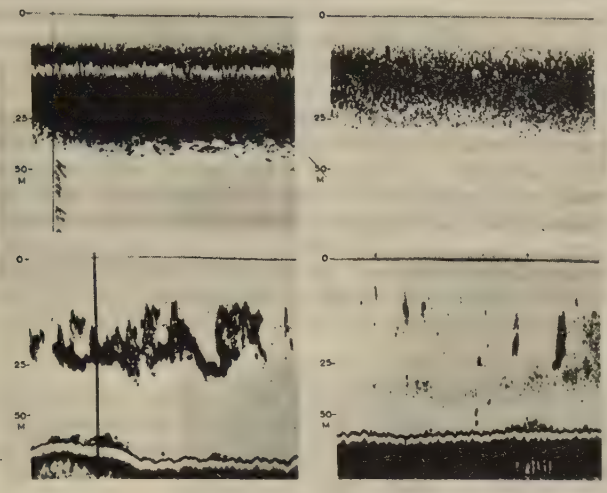


Figure 44 A - Echo sounder records of different types of layers and schools of small herring.

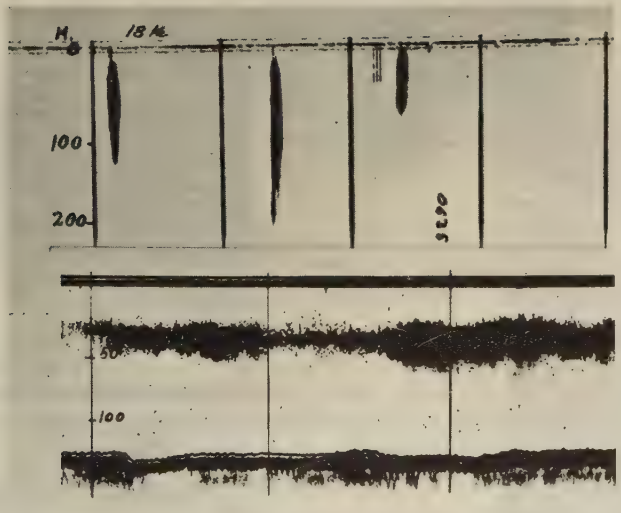


Figure 44 B - Echo sounder records of schools and layers of large adult herring.

A usual feature of layer type traces which are often produced by fish is the presence of single fish traces at the upper and lower borders of the layer. This is clearly shown in Figure 44 for small and large herring. This feature can be used to distinguish layer traces produced by fish from those of smaller organisms (fish larvae and other plankton organisms), whose individual target strengths are below the detectable limit of the echo sounder (see below). Further measurements of the signal strengths from the individual targets may sometimes assist in the identification of the fish present in the layers.

Well-defined schools of pelagic fish do not usually "thin-out" at the edges as with the layer traces. This is shown by the typical traces of herring schools in Figure 44 B (upper trace) and again in Figure 45 which shows schools of anchovy. A typical feature of echo records of dense pelagic schools is that its trace is often followed by a "tail" of sound reverberation. The sound-pulse is partly scattered inside the school and some of it is reflected back to the transducer even after the return of the direct echo of the deepest part of the school. The height of the trace of a school is, therefore, not a direct measure of the true vertical extent of the school. The reverberation can be distinguished in Figure 45 and also quite clearly by the upper trace in Figure 40.

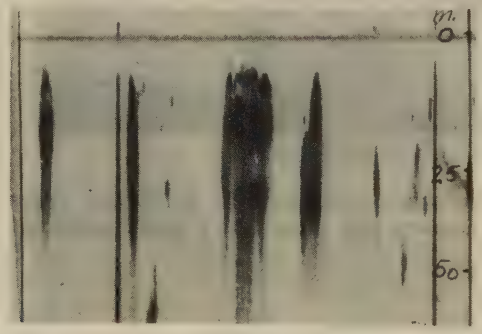


Figure 45 - Echo sounder record of dense school of anchovy.

Many fish species form schools in daylight and disperse into diffuse layers in darkness. These layers often allow recording of single fish traces. Examples for young and adult herring are shown in Figure 44; others, for cod and anchovy, are shown in Figure 46.

(A) (B)

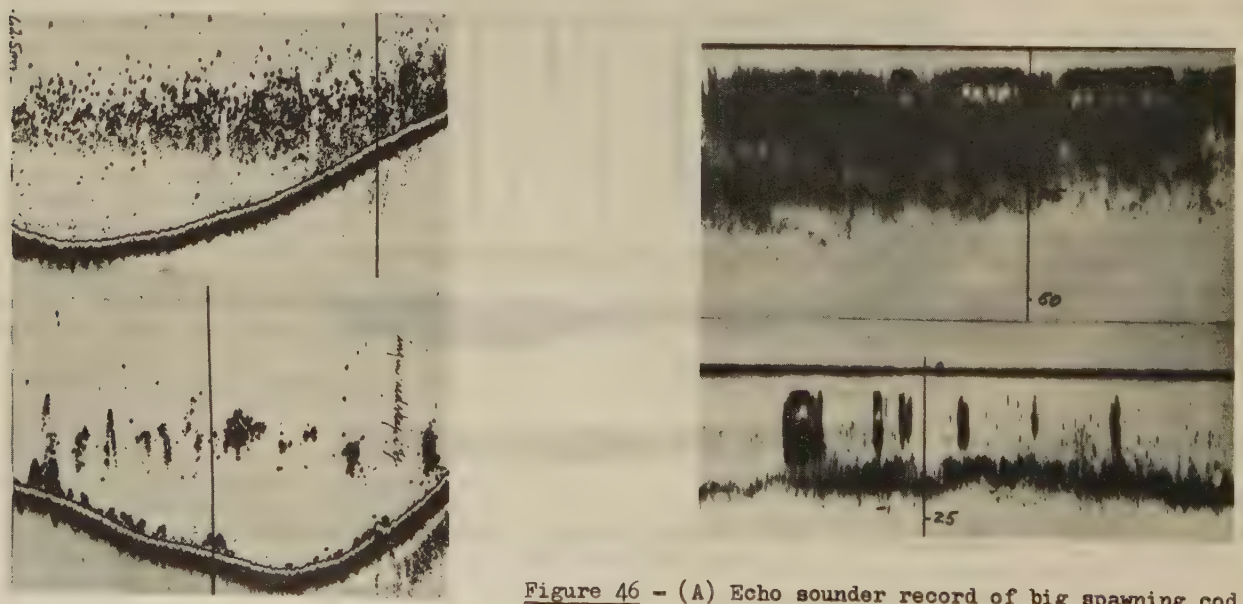


Figure 46 - (A) Echo sounder record of big spawning cod on the Lofoten Banks in layer during the night (top) and in schools during daylight (bottom). (B) Echo sounder records of anchovy. Top: in broad layer together with thinner plankton layer underneath during the night. Bottom: recording in the morning in the same area where the anchovy is now schooling, but plankton still in layer.

In addition to the layer-type traces recorded by fish concentrations, described above, other types of diffuse layer traces are also commonly produced by dense concentrations of smaller organisms such as fish larvae and other plankton organisms, often associated with a discontinuity layer in the water column. They appear as very finely grained "clouds" or "layers" and they are often recorded over large areas. In general such layer traces are produced by organisms whose individual target strengths are below the detectable limit of the instrument, but when occurring at high densities produce the characteristic diffuse traces. In this respect, they differ from the layer-type traces produced by fish in not showing records of individual targets in association with the main layer traces. Furthermore, the character of the trace does not change significantly if the vessel slows down or stops.

There is a graduation in the character of layer traces from this fine diffuse type to the layers produced by adult fish. 0 group fish, for example, are often distributed within fairly narrow depth limits and are, therefore, recorded as layer traces, but, like the traces of larger fish, they can usually be distinguished from the finer type of trace produced by fish larvae and other small organisms by the presence of individual traces in association with the layer trace. Further, the traces of 0 group fish which are of a layer type in darkness usually change to a more discreet school type trace in daylight.

An interesting echo record which appears as a diffuse layer is that of deep sea shrimp. It is well known that they rise from the sea-bed at night and the typical record obtained with a high sensitivity instrument from such a ground is as shown by Figure 47.

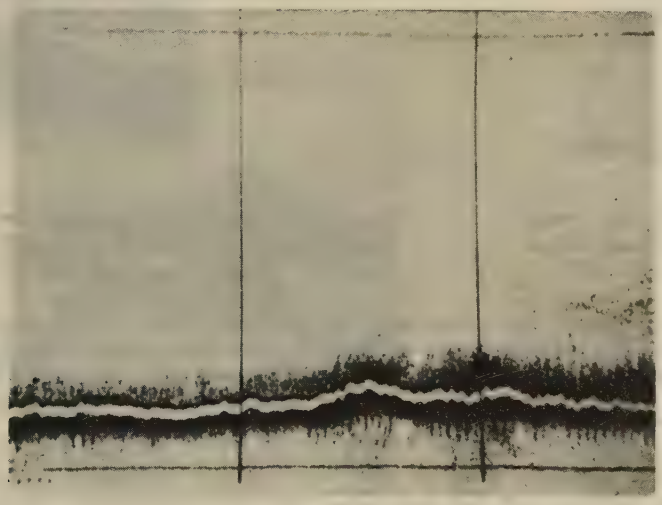


Figure 47 - Typical echo sounder record obtained from a fishing ground for deep sea shrimp at night and which shows shrimp lifting off the bottom.

A phenomenon of minor importance, which may puzzle an observant operator should be mentioned here. When surveying an area where small dense schools occur in the upper water layers, the side-loops of the echo sounder transducer may produce echoes which will take the form of long inverted v-shaped traces on the recorder. The phenomenon can be checked with a sonar instrument.

1.4 Records of fish close to the sea-bed

Fish which are very close to the sea-bed are more difficult to detect than pelagic fish because of the additional complications of distinguishing between fish and bottom echoes. This is illustrated in Figure 48, which shows that there is a "dead field" in the sound beam close to the sea-bed. If the bottom is uneven, the extent of the dead field increases.

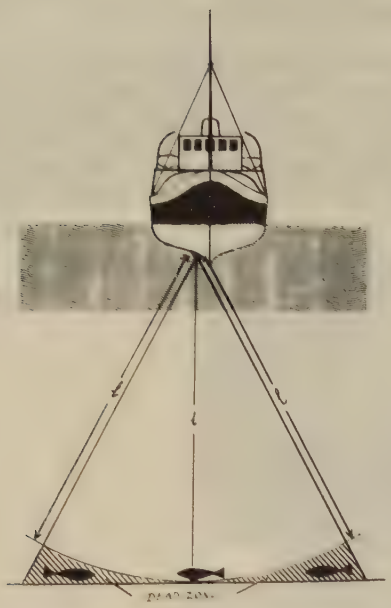


Figure 48 - Diagram illustrating the "dead field" in the sound beam close to the bottom.

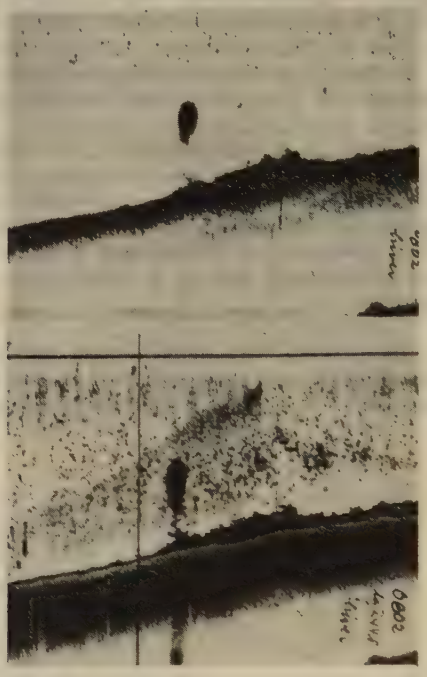


Figure 49 - Echo sounder records of the same target with and without white-line effect.

Because the paper recorder presents both fish and bottom signal as a black signal, the fish and sea-bed signals become confused. The "white-line" system of presentation assists in distinguishing between them by separating the sea-bed signal from the weaker signal of fish close to it. This is shown in Figure 49 in which the upper trace shows fish and bottom signal confused and the lower one their signals separated by the "white-line effect".

If fish are very close to the sea-bed, even if the "white-line" system is used, it may still not be possible to distinguish their echoes from the sea-bed. An example is shown in Figure 50.

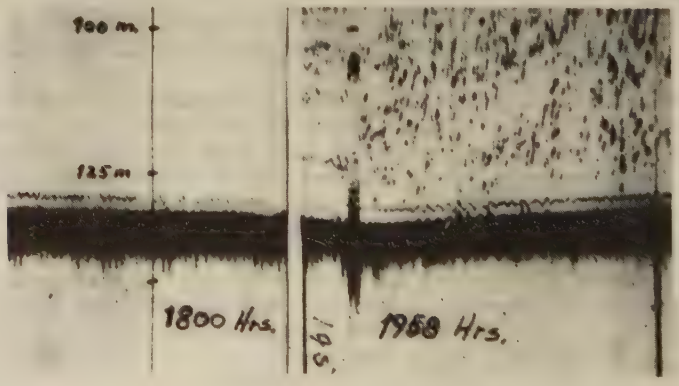


Figure 50 - Echo sounder records from hake trawling with good catches during afternoon (left) and showing hake lifting off the bottom in the same area after sunset.

The size of the dead field can be reduced by reducing the width of the echo sounder beam and/or the pulse length. With a pulse length of 2-3 inches, a fish like a cod should always be detected at least on the axis of transmission. The problem may be more or less completely solved in future with the use of sector scanning sonars (see Chapter 6).

One possible way of detecting fish close to the sea-bed is to use an echo sounder with a "slanting" sound beam that hits the sea-bed not vertically but at a relatively low angle. Then, echoes from fish near the bottom may, under favourable conditions, be distinguished from the relatively weak bottom echo.

1.5 Sources of extraneous and spurious echo records

The proper functioning of an acoustic instrument may be affected, or at times, completely prevented, by various types of "noise" sources on board the vessel. They may be of electric or acoustic origin and the problems connected with them are to a great extent related to the skill and care used during the installation of the equipment in choosing the location of the transducer. One of the most common of these sources of "noise" is propeller interference. Propeller noise will show up in a regular pattern and is often more prominent at a certain number of revolutions or at special pitch-settings. An example is shown in Figure 51.

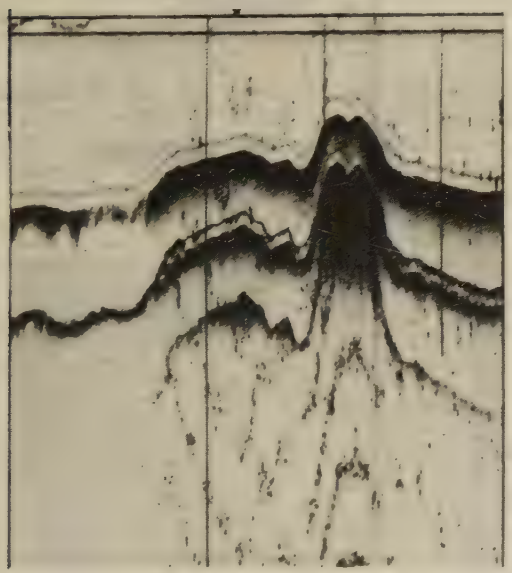


Figure 51 - Echo sounder record showing interference from propeller noise.

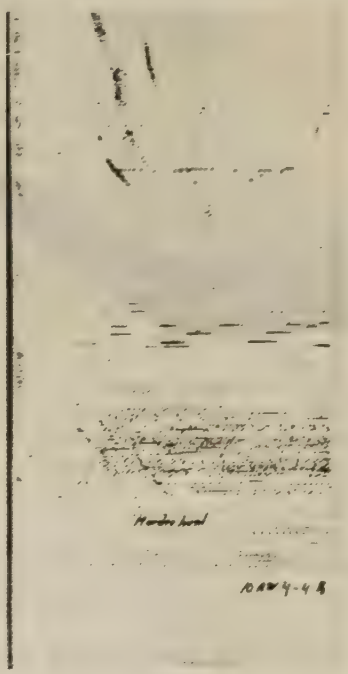


Figure 52 - Signals produced by a school of whales on a horizontal echo ranging recorder.

An important type of interfering echo is the side-echo produced by side-loops from a steeply sloping sea-bed. In narrow and shallow waters these may look like fish schools. In special cases the largest part of the sound energy may be reflected away from the bottom at a low angle so that it does not reach the ship and the echo that is picked up by the transducer may show up as a diffuse shadow more like a fish school than a distinct bottom echo. The dead field in the sound beam is also increased when passing a very steep bottom inclination.

Whales produce sounds in the sea which are recorded on acoustic instruments. Figure 52 shows various types of "pipes" and "squaques" produced by a school of whales on an echo ranging set. Similar signals are also recorded on echo sounders.

Finally it is worth noting that air-bubbles in the water immediately under the transducer may completely prevent the emission of the sound. This may occur when the vessel is pitching heavily in bad weather, and also when the ship crosses its own wake when going astern.

2. HORIZONTAL ECHO RANGING SONAR RECORDS

2.1 General characteristics

The important functions of horizontal echo ranging sonar in survey work on pelagic fish is that the area covered by the search can be much greater than that covered by a vertical echo sounder, and additional information can be obtained on the behaviour and distribution of the fish.

Echo ranging records are fundamentally different from those of echo sounders, but to an inexperienced operator, it may still be a help to think of this equipment as a "horizontal echo sounder".

An important feature of most of these instruments is that the transducers can be trained in any direction from the ship and the appearance of the echo traces differ accordingly. Figure 53 illustrates the typical patterns of records obtained when the transducer is fixed in a forward direction and at 90 degrees to starboard (or port) respectively. In shallow water an uneven sea-bed will give distinct echoes and the figures show the traces produced by three ridges of the sea-bed with the transducer in the two positions mentioned above.

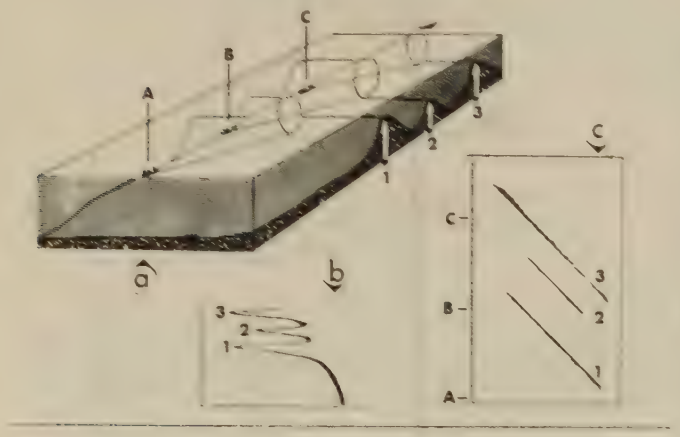


Figure 53 A - (a) A vessel with the echo ranging sound beam fixed in forward direction.
(b) Depth sounder recording of the same area.
(c) Echo ranging recording of the same area.

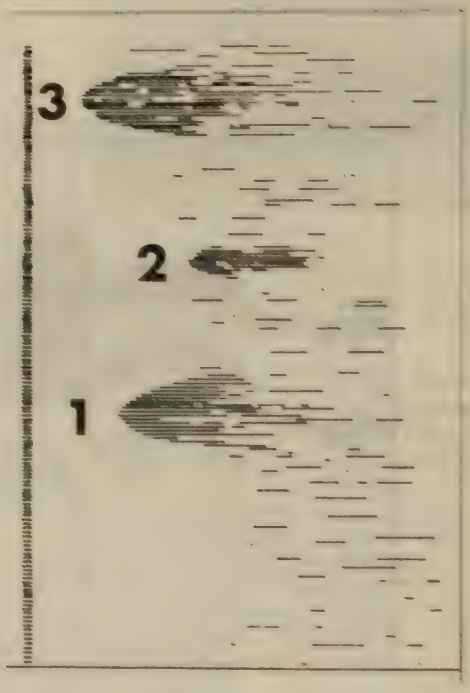


Figure 53 B - Echo ranging record from the same area as shown in A, but with sound beam fixed at 90 degrees to starboard, or port.

In the forward position of the transducer, the trace approaches the zero line until it disappears when the target passes underneath the bottom part of the beam. This depends of course on the depth of the target as well as on the beam angle. With a known beam angle the depth can be approximately estimated which is of some use for assessing the depth of fish schools. It is furthermore evident from this figure that the rate of approach is indicated by the angle between the trace-line and the zero line, and it depends on the relative movement of the vessel with respect to the target. Knowing the vessel speed, one can estimate theoretically at least, the movements of the target, but in practice movements of fish schools can best be observed with echo ranging sonar from a stationary vessel or by circling around a school and observing its position in relation to the wake of the ship.

Figure 54 illustrates schematically the recording of a fish school by echo ranging equipment when fixing the beam at 90 degrees to starboard. It is obvious that the width of the trace in the lengthwise direction of the recording paper depends not only on the size of the fish school, but also on the horizontal beam angle, on the speed of the vessel and on the paper speed.

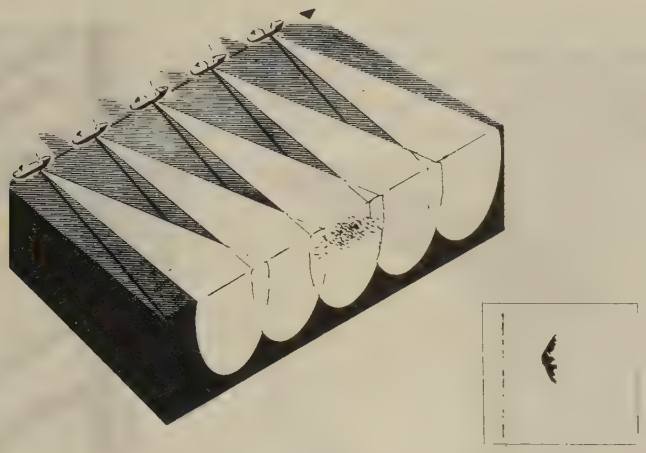


Figure 54 - A vessel passing a school of fish with the sound beam (transducer) fixed at 90 degrees to starboard.

2.2 Echo ranging records of the sea-bed

In contrast to the echo sounder the horizontal echo ranging sonar can usually not give much useful information on the sea-bed, since it is recorded by a normally operated echo ranger only in relatively shallow waters. Figure 55 shows a record containing various types of bottom echoes. The first trace (A) following the zero line is the side-loop echo from the bottom. This will correspond more or less directly with the true bottom depth. The second heavy trace (B) is the echo from the main beam where it hits the bottom at some distance from the ship.

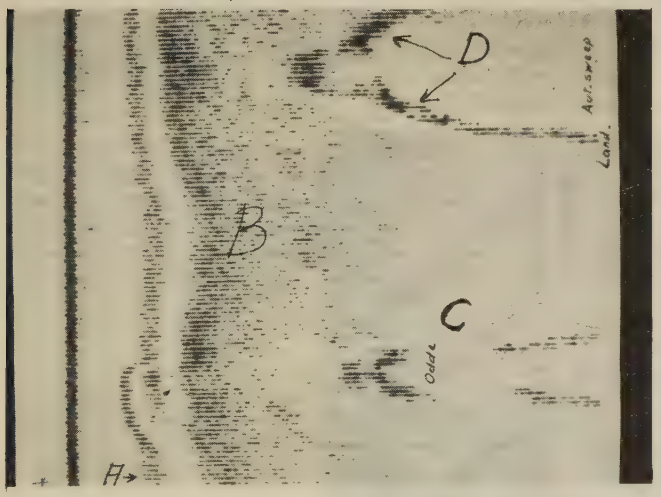


Figure 55 - Record of echo ranging echoes from the sea-bed and the shore.

Bottom echoes are easily recognised by comparison with the depth recorded on an echo sounder and by the fact that they do not vary significantly with changes in the training of the beam. Shore echoes and echoes from peaks and ridges on the sea bottom may, under certain conditions, give rise to greater difficulties of identification. However, for his classification of echoes, a trained operator makes use not only of the graphical record, but also of an audible signal by which it is often possible to distinguish between echoes from different types of targets.

2.3 Records of fish

The appearance of fish records on the horizontal echo ranger recorder will differ with the search programme that is being applied. A normal programme for the widest possible coverage is to search between about 60 degrees port and 60 degrees starboard with sound emissions at every 5 degrees. Modern instruments have automatic search programmes of this type. The type of records obtained when passing a number of fish schools with a side to side sweep is shown in Figure 56. Traces are produced as the beam passes the schools in 5 degree steps. The same target may appear two or more times in the echo record depending upon its distance from the ship's course and the range at which it was first detected. This type of search programme is, therefore, not suitable for obtaining a count of the number of schools recorded and assessing their range

and roughly their size. However, it is the most effective detection programme and Figure 57 shows a record of a side to side sweep, during the process of a vessel homing on to fish schools.

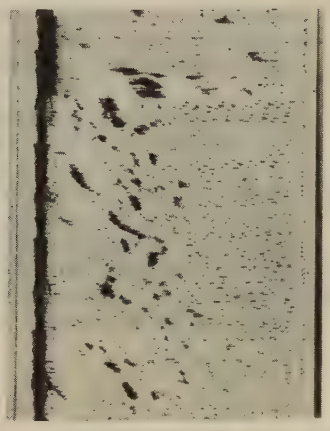


Figure 56 - Echo ranging record when passing a a number of good recordable fish schools with a search programme of side-to-side sweep.

Figure 57 - Echo ranging record of side-to-side sweep interrupted by instances of the vessel turning towards and approaching schools.

Figure 58 shows echo ranging and the subsequent echo sounder records of schools which were approached and passed over. It will be noted that the size of the echo sounder traces of the schools do not always correspond to the strength of the echo ranging ones. This is usually because it is difficult to "hit" the school with the ship so that it passes through the centre of the echo sounder beam.

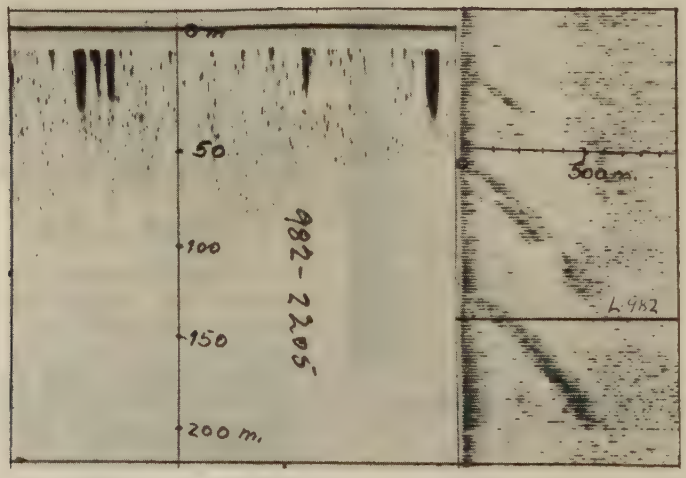


Figure 58 - Records on echo ranger (right hand trace) and echo sounder (left hand trace) of schools that were approached and passed over by the vessel.

A survey programme frequently used for pelagic schooling fish is to have the transducer at a fixed angle of 45 to 50 degrees to port or star-board. This will allow a reasonably good coverage over the course steamed while at the same time providing relatively long traces of the targets and hence information regarding their number and classification.

Some horizontal echo ranging instruments have, in addition to their full range scale, a short scale for use at distances of a few hundred metres. Figure 59 shows a record of a fish school that is being approached at the full range. When closing in, the short range with a higher transmission rate and faster pen speed was used. The shorter range should also be used when searching or surveying in water where sonar conditions are poor so that the effective range of coverage is severely restricted. The higher transmission rate of the shorter range interval will then ensure more echoes and thus more information from each target.

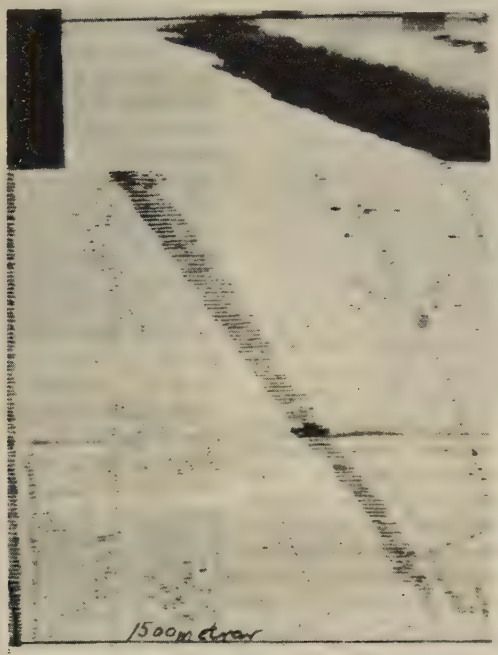


Figure 59 - Echo ranging record of a fish school being approached using first (left hand trace) the full range of the instrument and later the short range (right hand trace).

If the transducer is tiltable or if a separate vertical transducer can be used, schools can be approached and then recorded vertically with the same echo ranging equipment. Figure 60 shows a record of this operation carried out with an instrument used for short range work. However, because the technical requirements of echo rangers and echo sounders are so different the use of a combined, dual-purpose instrument is not recommended. Simultaneous operation of the two types of instruments is usually advisable.

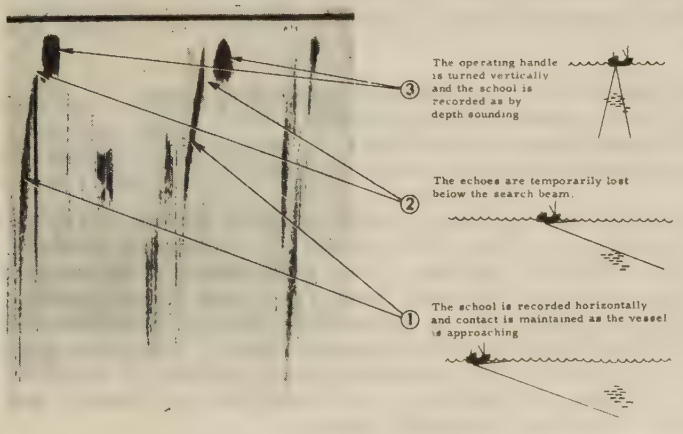

3
The operating handle is turned vertically and the school is recorded as by depth sounding
2
The echoes are temporarily lost below the search beam.
1
The school is recorded horizontally and contact is maintained as the vessel is approaching

Figure 60 - Records and schematic diagram of how schools can be approached with horizontal sound beam and recorded vertically with the same beam in instruments with tiltable transducers.

Under favourable conditions, schools of fish close to the sea-bed can be detected by echo ranging equipment. The sea-bed must be reasonably level and smooth. Figure 61 shows a record of fish schools being approached by a vessel using different echo ranging scales (left) and the subsequent trace of the schools on an echo sounder (right).

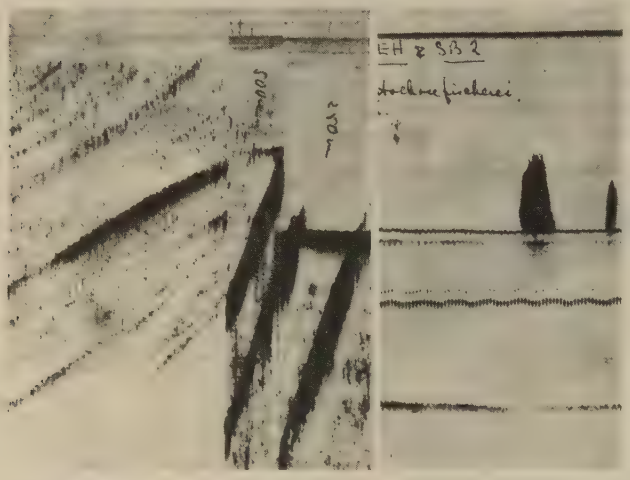


Figure 61 - Echo ranging and echo sounder records showing fish schools on the bottom being approached using three different basic sonar ranges and the same schools appearing on the vertical echo sounders. Note that the sonar traces of the fish schools disapper just after the bottom echo from the main sonar beam appears on the record. This is because the schools are located close to the bottom.

Finally, reference should be made to another type of recording of echo ranging signals, i.e. their presentation on a P.P.I. screen. This has the advantage of giving a correct, two-dimentional image of the distribution of the targets relative to the vessel, similar to the well-known picture obtained on a radar screen.

In Chapter 1, anomalies in the propagation of the sound by refractions of the sound beam under special oceanographic conditions have been described. Such refractions may greatly affect the range of detection. The vertical temperature gradient is the factor of greatest importance for the refractions and hence the range. A bathythermograph record of the upper water layers may, therefore, give important information for assessing the effective range. Generally speaking, echo ranging conditions are best when there is no vertical temperature gradient or a slight increase with depth. This condition will, in most cases, occur in winter and early spring. Summer conditions with a warm surface layer and a sharp thermocline near the surface may result in a considerable reduction of the range because of a sharp refraction of the beam downwards. The approximate, effective range in an area can, in practice, be assessed empirically quite rapidly if a rough evaluation of the target strength of the recorded schools can be obtained, for instance from subsequent echo sounder records, or from echo ranging contact at a very short range. One should always keep in mind that at some distance the strength of the echo does not only depend on the target strength of the object that is being recorded, but also very much on the sonar conditions in the sea.

2.4 Records of echoes from extraneous and spurious sources

Various types of disturbing signals arising from electric or acoustic "noise" produced on board the vessel itself, may affect echo ranging records in the same way as with echo sounder ones. There are, however, a number of types of disturbing "non-fish" records that are peculiar to echo ranging records. Since signals may in most echo ranging sets be presented as audible sound as well as paper records, the transducer-receiver units take the function of a microphone by which certain kinds of underwater sound may be heard. Propeller noise is one of the strongest and most conspicuous of these. The propeller noise of one's own ship may, incidentally, be used as a rough check that the training indicator of the transducer is correctly set: the noise should have a maximum when the transducer is pointed directly astern.

Sea-water containing small air or gas bubbles gives good echoes, and records of the wakes of steaming ships may easily be mistaken for fish schools. In a rough sea, with big breakers, aeration of the water may cause the sonar beam to be reflected. Three or four good echoes may be received from such breakers, even at considerable distance, but the contact is usually quickly broken.

Reverberation is the shifting sound heard after a pulse transmission, and the small dots and dashes recorded on the echo record. Thus, it consists of a sequence of small echoes. It is caused by echoes from small sound scatterers in the sea. Over deep water, reverberation can give useful information on the effective range in an area because these faint echoes are usually only produced in the surface layers and not from a beam refracted downwards. Figure 62 shows two records of reverberation, one indicating a long and the other a relatively short range. The sound pitch of the audible record of reverberation (and other echo signals) on a steaming ship differs in relation to the training of the transducer relative to the course of the ship. It is high in the forward and low in the astern direction because of the Doppler effect on the sound waves.

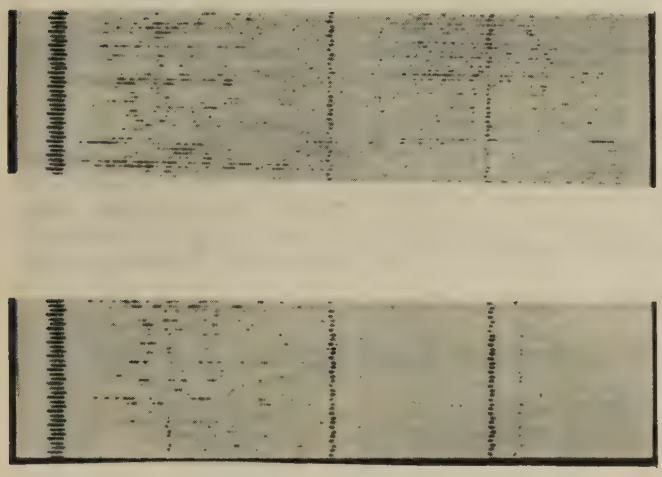


Figure 62 - Sonar records demonstrating long and short reverberation.

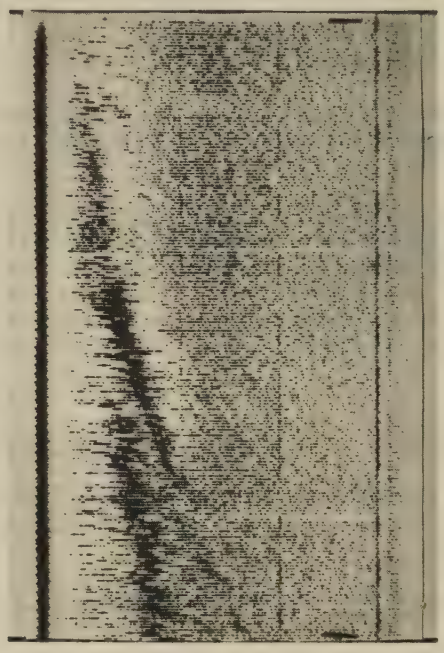


Figure 63 - Sonar records of stratal echoes.

Large vertical or horizontal temperature gradients in the sea may give rise to stratified echoes. Because of the irregular, often wavy, pattern of such strata, the echoes from them may vary considerably with distance and they may on occasion be confused with stationary targets by an inexperienced operator. They are, however, usually not much affected by a change of direction of the beam, being detectable around 360 degrees, and they do not give the sharp and distinct echoes characteristic of fish schools. Figure 63 shows a record of stratified echoes; when they are present the range of the equipment is often short.

Finally, it is worth mentioning the occurrence of interference from other acoustic instruments. Even if working on a different sound frequency, an echo sounder may give rise to interference on an echo ranging equipment and vice versa. Where several vessels using acoustic instruments operate within a small area, interference may be severe but neighbouring boats are usually visible and the interpretation of the records is thus usually possible.

CHAPTER 4

THE IDENTIFICATION OF TARGETS

B.B. Parrish and R.E. Graig

1. GENERAL

The problem of identifying the echoes obtained from a particular species (or group of species) of fish is clearly of major importance in determining the accuracy with which echo surveycan be applied in studying them quantitatively.

It will be evident from the description of echo records given in Chapter 3 that there are no general rules which will allow a species of fish to be identified directly from its echo trace. This is because there is no species of fish so consistent in its behaviour as to give at all times the same echo pattern, and because different species of fish exhibit similar patterns of distributional behaviour and so give rise to similar echo records. Therefore, the kind of information that can be extracted with certainty from such records can usually only be exemplified by such statements as:

(a) This trace definitely represents a dense pelagic school not more than 30 m across.

(b) This trace definitely represents a large dense pelagic school at least 300 m in extent.

(c) This trace represents either a pelagic distribution of large single fish or a pelagic distribution of small fish shoals not more than 10 m each in extent and not more than 2 m in vertical extent.

(d) This diffuse trace represents either a dense layer of planktonic organisms, or a layer of fish widely dispersed.

It is true that in some instances the element of doubt about the species giving rise to particular types of echo record in a survey area is negligibly small, as in the case of some pelagic schooling species, such as a herring population which, at the time,is being actually exploited by, say,a purse seine fishery, and is shown to be the only pelagic, schooling species in the area in question. In such a situation the "plume-shaped" traces, characteristic of a fish school can be treated with confidence as being herring. However, in many situations, where a number of species of fish occur together and have a similar distributional behaviour, doubts about the identity of the echo records will only be dispelled after the application of several methods which give supporting evidence. Furthermore there will also be examples in which different methods suggest different answers, and so it may not be possible to reach definitive conclusions.

2. METHODS OF IDENTIFICATION

2.1 Catch sampling

One obvious method of identification, which is widely used in association with echo survey is to sample the fish (or other organisms) giving rise to the echo traces with appropriate catching gear. These methods are widely employed, use being made either of special sampling gear from research vessels, or, if appropriate, of the catches taken by a fishery in the survey area. The accuracy of such methods is, of course, governed by the selective properties of the sampling gear, as exemplified for example by a large mesh trawl. Efforts must be made to reduce such selectivity to a minimum, such as in trawl sampling by the use of small mesh covers on the cod-end. Even so, it must be recognized that selection by factors other than the cod-end mesh size may be so severe as to invalidate the study. It is therefore of major importance that the choice of sampling method should be considered critically for each type of echo survey situation and, if necessary, a combination of sampling gears, relevant for different types of fish or other organisms should be used. Also, wherever possible, other independent direct methods of sampling or identification should be employed as well as the caching gear.

2.2 Other methods of identification

Among other methods of sampling or identification are the following: (i) the use of explosive charges, (ii) the use of underwater photography, (iii) direct observations by divers or men in underwater vehicles, and (iv) television. To these might be added a method which has not yet been reported, but seems to offer some useful features, i.e. small scale electrical fishing.

(a) Use of explosives

Many species of fish, if killed or stunned by explosives, will rise to the surface and float for a while. These can be collected for identification by a small, hand operated net used from the ship or from a small boat. One successful method of operation is to mark the position of the echo trace with a suitable float and to detonate a small towed charge electrically. A merit of the use of explosives is that it is a very quick operation compared to any commercial fishing method, and it is highly specific as to position. A 100 g charge will stun fish up to 12 or 15 ft distance and so the resultant catch can be fairly definitely associated with the echo sounder recording. Small charges such as this are effective in dealing with shoals of fish down to about 20 m depth.

In deeper water, large charges, perhaps of 50 kg or more are necessary, and such large explosions are scarcely to be recommended unless the staff concerned are familiar with explosives.

(b) Photography

Cameras, suspended in the sea, or attached to fishing gear, offer a means of adding information to direct catch sampling. Suspended cameras are only rarely useful, since avoidance reactions may occur, and it is difficult to ensure coincidence of camera, and the targets giving rise to the echoes. (The camera can usually be seen on the echo sounder, but coincidence of its echo trace with the fish trace only confirms equality of range.) However, with dense and relatively inactive fish concentrations, apparently typical of fish in very cold water, very useful identifications have been reported by the use of cameras suspended in the sea (e.g. Truskanov and Scherbino, 1964).

Cameras attached to fishing gear, particularly to the demersal trawl, are very effective in checking the fish population traversed and herded by the net. It is not uncommon with this method to obtain evidence of the presence in the vicinity of the fishing gear of species which by virtue of their activity of small size, are unrepresented in the catch.

(c) Direct observations

Divers, using SCUBA equipment, are extremely efficient observers in many instances where light is adequate and visibility good. There are severe limitations on operational depth, and it seems surprisingly difficult, for instance, for a diver to contact shoals of active fish such as herring. There are also fairly severe limitations on open sea working in any but the best of weather.

Some of these limitations will be overcome by submersible vehicles of one sort or another - self-propelled or towed from the parent ship. Submersibles are not yet commonly enough available to suggest this as a normal identification method.

(d) Television

This method has great attractions superficially, but its chief advantage over the camera is the much larger observing time available. Against this, its relative frailty and clumsiness makes it usually a less appropriate choice. If it should prove possible to miniaturize cameras of high sensitivity to low light values, the balance of advantage may be shifted somewhat in favour of television.

It is evident, therefore, that at present the difficulties of identifying reliably the targets giving rise to echo traces may be substantial, and they must be considered carefully for each situation in which echo survey methods are to be applied, especially in quantitative abundance studies. Work currently in progress on the acoustic properties of fish, especially on their swimbladder resonance, properties, may yield results which provide a direct method of identifying species of fish acoustically. Also, the patterns of sounds produced by some species of fish may prove useful for this purpose. However, for the present, use must be made of a combination of the independent methods outlined above.

CHAPTER 5

THE ESTIMATION OF FISH ABUNDANCE

D.H. Cushing

1. GENERAL

Fishery scientists have a need for population estimates made independently of fishery statistics of catch and fishing effort, and methods are also required for the rapid exploration of unexploited fish stocks. Search by exploratory fishing is slow, expensive and, because fish sometimes migrate as fast as the rate of exploration, this method may also be unreliable. A method of sizing and counting fish with an echo sounder could be used for the exploration of unknown stocks and for making estimates of the well-exploited stocks independently of catch and effort statistics. This chapter describes the development of reliable methods of sizing and counting fish.

Any stock analysis presupposes that the fish to be counted can be identified. While acoustic methods might become available for identification they are not so at present and so some auxiliary methods have to be used. These are described in Chapter 4. Difficulty is evaded by always expressing the acoustic results as quantity of fish. Where the acoustic survey is a simple one, estimating the relative abundances in different areas, the proportions of different fish species can be estimated from the catches taken at intervals during the survey. Such estimates of abundance can be supported by a considerable body of knowledge of the general biology of the fish. For example, Lee (1952) showed that cod in the Barents Sea in June tended to be confined to the warm side of the 2°C isotherm on the bottom. When Richardson et al. (1959) made an echo survey in the same area, the echo patches were limited in distribution by this isotherm. In interpreting the echo survey, the biological information relating temperature to the distribution of cod was of great value.

There are a number of ways of estimating the quantity of fish trace from an echo survey. Perhaps the easiest way is to measure the widths of traces of fish on the paper records at its widest part. Essentially the method examines each transmission for the presence or absence of echoes. This method cannot be used to determine the absolute abundance of fish directly, but it has been used to give estimates of relative abundance. It has been applied widely in a number of investigations, especially of pelagic fish (e.g. Cushing 1952). It is sometimes possible to obtain relative abundance estimates especially for pelagic species which form a compact school of reasonably uniform size by counting the number of discrete traces on the paper record rather than by measuring the width of the traces. If independent estimates of the average number of fish in the schools are available, as for example from the statistics of catches in a purse seine fishery, absolute estimates of abundance can be obtained by this method.

In using this method, it is assumed that the depth of water in the area surveyed does not vary too much and that the fish are randomly distributed in depth throughout the survey. This is because the sampling volume of the echo sounder varies with depth for a target of a given size, within its range of detection. In practice, differences in the signal strength due to depth are often less than differences due to relative abundance. The signal-to-noise ratio must be sufficiently high to allow the fish signals to be distinguished from noise with reasonable confidence. An echo from fish will usually be received from the same range two or three times, or more, in successive transmissions. The trace-to-trace correlation gives the signals a distinct coherence. If the signal-to-noise ratio is high, it is very unlikely that "noise" would fulfil this condition. "Noise", of course, increases with increasing heavy weather and so the signal-to-noise ratio decreases with rising seas, until a point may be reached when the fish signals cannot be distinguished from noise.

In using the echo sounder for estimating relative abundance by these methods it should be calibrated. Methods of calibration are dealt with in Chapter 2.

2. COUNTING OF INDIVIDUAL FISH

The measure of relative abundance described above makes no distinction between types of trace. However, it is quite easy to distinguish traces of individual fish from traces of fish shoals. A trace from an individual is distinguished by its constant pulse length during the period of recording. The pulse lengths from a number of individuals in a school must overlap in range and so the pulse length received from a school is not only greater than that from an individual, but it varies during the period of recording. The individual fish trace has been named the "fingernail" trace and is illustrated in Figures 41 and 42 in Chapter 3.

If fish can be recorded as individuals, it follows that it may be possible to obtain estimates of absolute abundance from echo surveys (see, for example, Hylen, Midttun and Saetersdal, 1961). The

estimates of absolute abundance made in this way will, of course, only apply to the depth range within which the individual fish can be detected by the echo sounder in use. It is important, therefore, that this depth, at which the signal from a fish of given size can no longer be detected, should be known. This is a function of the target strength of the fish and the acoustic properties of the echo sounder, as indicated by the sonar equation defined in Chapter 1.

3. THE STATISTICAL TREATMENT OF SIGNALS

An essential requirement for estimating abundance by this method is knowledge of the sampling volume of the echo sounder beam. The determination of this parameter is outlined below.

As shown in Chapter 1, the directivity coefficient, δ, decreases in angle Θ from the axis to the first minimum, δ_{min} (0.05, or 0.10 of the signal on the axis). Numbers of fish, however, increase as the square of the angle Θ. Figure 59 shows the two distributions in angle Θ. They can be multiplied together to give a product distribution, the broken line in the figure. The mean of this product distribution in angle is the mean angle, Θ_m, at which signals from the fish are most commonly received.

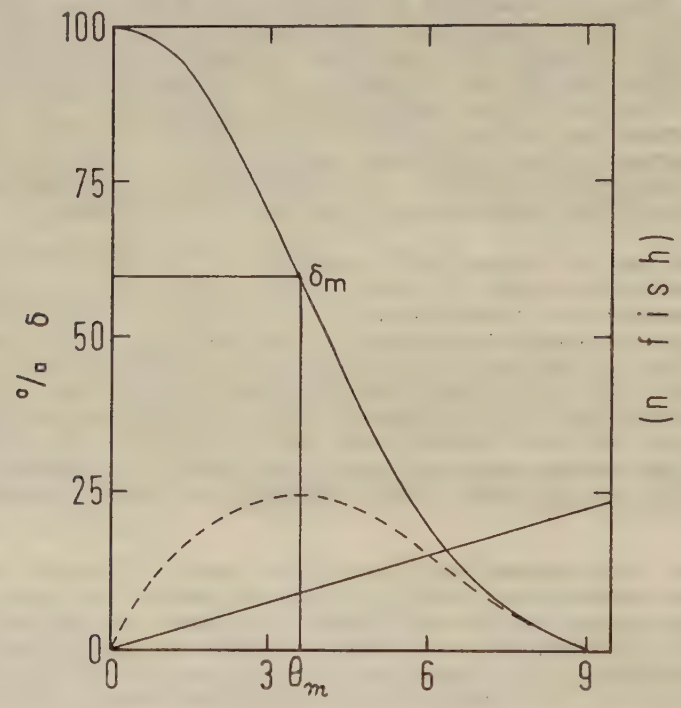


Figure 64 – Distribution of the directivity coefficient, δ, in Θ, the angle from the axis of transmission (curved, full line); distribution of fish density in angle Θ (straight line); the product distribution by multiplying fish density by δ in steps of Θ (broken line)

The sampling volume of an echo sounder is described by the maximum range (R_{max}) of the target and the beam angle (Θ). At a lesser range, R_1, the same signal is recorded as a minimum recordable signal at δ_{min} (corresponding with the angle Θ_{min}). Therefore

$$R_1^{-2} = R_{max}^{-2} \cdot / \delta_{min} \quad \ldots\ldots\ldots\

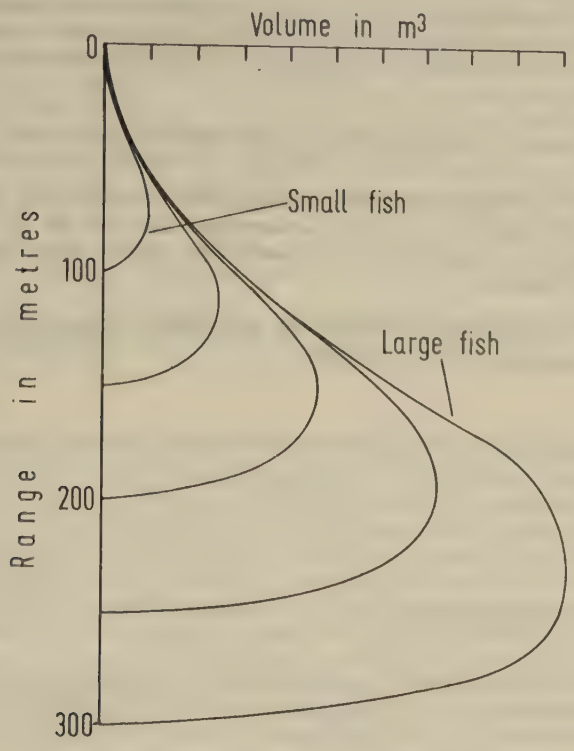


Figure 65 - Representation of the sampling volumes for fish of different sizes and target strengths.

The sampling volume can be split into slices, range shell volumes.

For a square transducer, the range shell volume, between R_1 and R_2 and out to Θ_{min} in angle is defined as

$$\frac{2}{3}\pi(R_2^3 - R_1^3)(1 - \cos\theta_{min}) \quad \ldots\ldots (37)$$

and, for a rectangular transducer, by

$$\frac{2}{3}\pi(R_2^3 - R_1^3)(1 - \cos\sqrt{\theta_\alpha\theta_\beta}) \quad \ldots\ldots (38)$$

where θ_α and θ_β are the angles subtended by the major ($R \sin \Theta_{\alpha\ min}$) and minor ($R \sin \Theta_{\beta\ min}$) axes of an ellipse at a range R.

The range shell volume is that in which a signal from a fish can be detected. It can be split into sectors of angle Θ. Each sector is multiplied by the appropriate directivity coefficient and the sum of all sectors, so weighted, is the effective volume sampled; it takes into account the chance of detection varying with directivity.

Any record of an individual target comprises a number of repeated signals in time. The numbers can be counted per unit time or distance. Thus for a vessel steaming for $\frac{1}{2}$ hour, at 9 knots, the number of effective volumes samples is given by

$$\frac{n.2R.\sin \Theta_{\beta\ min}}{9000} \quad \ldots\ldots (39)$$

where n = number of fish, and R = the depth. So the number of individuals per half hour steamed can be expressed as $M/_m 3$. However, there is a bias due to the overlap of successive volumes. This bias can be considerable under certain circumstances and is described in an Appendix by J.G.K. Harris to Cushing, 1968.

Number of fish are counted in unit distance steamed and could be expressed as numbers per total volume samples in that distance, V_T. This volume is complex, its width being determined by Θ_α, its length by the distance steamed and its height off the bottom on the axis by Θ_β. There is also an error of the discontinuity of the repeated signals in time, a downward bias of 6% in 50 fm and 2% in 300 fm. The statistics of signals in a number of range shell volumes are fairly easy to handle; those for the total volume, V_T, are difficult to handle.

The same system can be used to estimate the sizes of individual fishes in a statistical manner. Signal strength is calculated for any size of fish from

$$V_{em} = \sqrt{k\frac{V_{sm}}{R^2}}\,\delta_m \qquad \text{(40)}$$

where

V_{em} = received voltage

V_{sm} = voltage of transmitted signal at source

At ranges greater than R_1, δ_m tends towards unity. So the signal strength is specified for any range as at an average position in the range shell. The points in Figure 66 are observed signal strengths (voltages) obtained on the continental shelf off South Africa and S.W. Africa from readings taken with a Kelvin Hughes "Humber" echo sounder in February 1966.

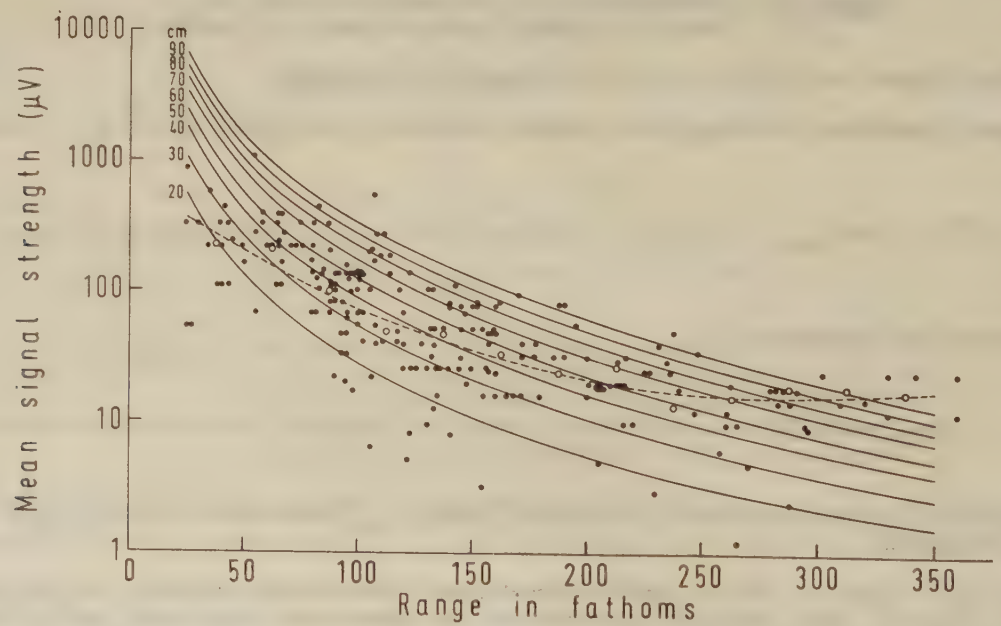


Figure 66 – Signal strength (in μV) of fish between 20 and 90 cm as function of range (full lines) calculated from the sonar equation, as at $T.R^{-2}\Theta_m$. The points represent observed values of signal strength in the four fathoms off the sea-bed. The broken line represents the trend of mean signal with range. The large black circle at 210 fm represents the size of fish (46 cm) in catches made by the commercial fleet during the echo survey.

Almost all of the echoes were from individual fish and it is seen that they lie in the range 20–90 cm. Indeed the broken line shows the average signal strength by depth intervals, the bigger fish living in deeper water. The large circle at 210 fm represents the mean size of fish caught by trawl during the survey in three different areas; it will be seen that this mean size of fishis very close to that estimated acoustically. In fact the range of sizes sampled by trawl and by echo sounder were very similar, ranging from 20–90 cm. As much as 90% of the trawl catches is composed of hake; so it appears that most of the echoes were received from hake.

It is also possibleto estimate the mean depth (or mean height above the bottom) using the mean angle, given by

$$R_2 - (R_1 - \tfrac{1}{2}(R_1 - R_2)) \cos \theta_m \quad \ldots\ldots\ldots\

CHAPTER 6

NEW DEVELOPMENTS IN SONAR TECHNIQUES

F.R. Harden-Jones and F. Hester

In the preceding chapters attention has been confined to the description of the constructional and operational features of the two main types of sonar equipment - vertical echo sounders and echo ranging sonars currently in wide use for fish detection in commercial fishing and in research. In this chapter consideration is given to some of the new sonar techniques which are currently coming into use, at least in research, and which present important potential advantages over the older equipment for many research, and in some cases also commercial fishing, purposes. The techniques dealt with are:

1. Electronic sector scanning sonar
2. Continuous Transmission Frequency Modulated (CTFM) sonar
3. Wideband sonar

1. ELECTRONIC SECTOR SCANNING SONAR

1.1 Basic system

As described in Chapter 2, in an echo ranging scanning system the receiving transducer is moved mechanically in azimuth to obtain the bearing of the target. However, scanning can be carried out electronically if the receiver is made up of a number of separate elements in the form of a linear array. The phase relationships of the echo reaching the separate elements of the receiver depend on the bearing of the target. When the target is on the acoustic axis in the far field, the signals received by the elements will also be in phase and if the outputs are summed they will add in phase to a maximum. But at all other bearings the signals received by the elements are out of phase and the summed outputs do not add up to a maximum. But it is possible to compensate for the phase differences between individual elements by introducing local phase shifts, so bringing the summed output of the whole array to a maximum. If the phase relationships of the outputs are suitably modified, the direction of maximum sensitivity of the array can be steered in azimuth without moving the transducer.

Methods which might be used to steer the receiver beam are as follows:

(a) by using a series of delay lines and a multiple switching device;

(b) by sweeping the outputs of the receiver elements by a frequency modulated carrier and passing them into a tapped delay line where a phase shift is introduced as a linear function of frequency;

(c) by suitable modulation of the outputs of the receiver elements.

Early developments in electronic sector scanning sonar made use of multiple delay lines and real time delays, but such systems are relatively crude. The sustem developed by the Department of Electrical Engineering of the University of Birmingham, England, uses a frequency-swept carrier and a single delay line, while the British Admiralty Research Laboratory, "Bifocal" system uses multi-stage modulation scanning (Voglis and Cook 1966).

Electronic scanning allows a wide sector to be covered very rapidly. For example, the British Admiralty Bifocal system has two modes of operation (the origin of the name Bifocal) which are analogous to the search and classified modes of the CTFM sonar. In the wide sector mode the Bifocal scans a 30° sector at 10,000 scans a second, with a range resolution of 8 cm and a bearing resolution of 0.3°. In the close-up mode the scanned sector is reduced to 10° and the scanning rate increased to 30,000 scans a second, the range resolution being 2.5 cm. These scanning rates are so fast that the whole sector can be covered within the duration of the pulse of the returning echo. "Within-pulse" scanning means that the whole width of the sector is, for practical purposes, viewed simultaneously so that no information is lost. The time taken to scan a sector therefore depends only on the range of maximum interest.

In both the Birmingham University and the Bifocal systems, range and bearing information are presented on a rectangular B. scan cathode-ray-tube rather than a PPI display. While the PPI display gives a true plan picture (ignoring geometrical distortion) this is obtained at the expense of the lateral compression of information at short ranges, which must reduce some of the advantages of a high bearing resolution. Some parameters of the Birmingham University and the Admiralty systems are given in Table 1.

TABLE 1

A COMPARISON BETWEEN THE PARAMETERS OF THE TWO ELECTRONIC SECTOR SCANNING EQUIPMENTS

	Birmingham University Equipment	British Admiralty "Bifocal" Equipment
Type	Delay line	Modulation
Source of data	Welsby et al. (1963)	Voglis and Cook (1966)
Operating frequency kHz	500	300
Beam angle of horizontal sector insonified	30°	30° (s) 10° (c)
Horizontal sector scanned	30°	30° (s) 10° (c)
Receiver beam width	1.0°	0.33°
Range resolution	10 cm	8.0 cm (s) 2.5 cm (c)

(s) = search or wide angle mode

(c) = classify or close up mode

1.2 The information given by sector scanning sonar

The data summarized in Table 1 shows that these electronic scanning systems have a very high range resolution and very narrow receiver beam widths. It is of interest to consider how these parameters can affect the detail of the display and the ability to resolve, or separate, individual targets. For an example let us consider the Bifocal equipment when used in the wide angle mode. The 30° sector is scanned in the horizontal plane by a receiver with a beam width of 0.33°. The range resolution is 8 cm, and the effective vertical beam width of the scanned sector is 7.5°. The volume under surveillance is therefore divided into a large number of compartments and the picture shown on the display is a mosaic. But it is important to note, as shown in Figure 67 that the horizontal and vertical dimensions of the compartments increase with range.

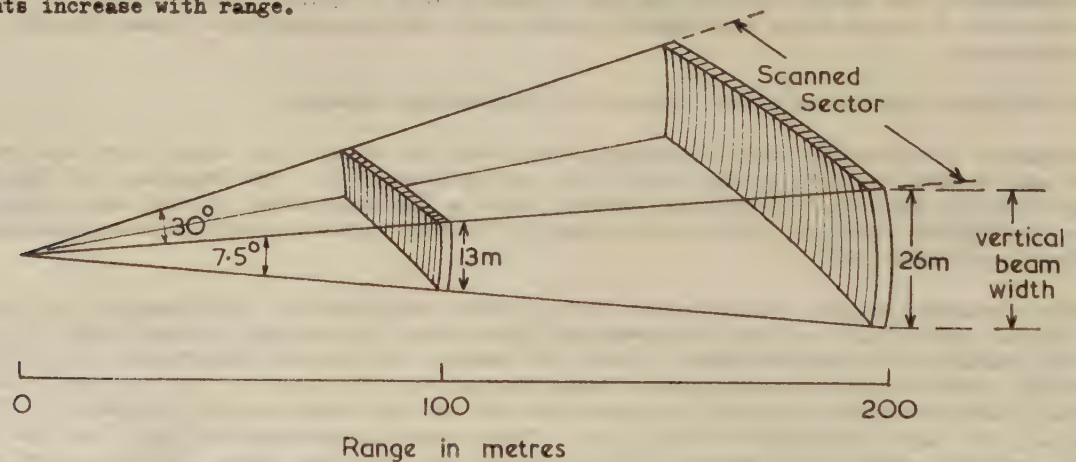


Figure 67 - Diagram to show the increase in the dimensions of compartment size, or scanning mosaic, with range. Scanning takes place in the horizontal plane over a 30° sector. The vertical beam width is 7.5°.

At 100 m, each compartment is 8 cm deep in range, 60 cm wide in azimuth and 13 m high in the vertical plane. At a range of 200 m the compartments are still 8 cm deep in range but are 120 cm wide and 26 m high. These compartments, which are slightly curved about the vertical axis, are the units of the mosaic of the cathode-ray-tube display. The detail shown in the display is thus a function of compartment size, and therefore range. If the sonar is reverberation limited, it is the volume reverberation (which could include surface or bottom reverberation) within these compartments against which the target echo must be detected. Two or more targets occupying the same compartment will be displayed as one target, and two targets of equal target strength occupying adjacent compartments cannot be resolved.

1.3 Trials with sector scanning sonar

Sector scanning sonar equipment has now been used in a sufficient variety of field and laboratory trials in connection with problems of fisheries science to demonstrate the potential value of this scanning technique for a variety of problems (e.g. Tucker, Welsby and Kendell, 1958; Tucker et al., 1959; Harden Jones and McCartney, 1962; Welsby, Blaxter and Chapman, 1963; Welsby et al., 1964; Tucker and Welsby, 1964; Voglis and Cook, 1966; Cushing and Harden Jones, 1966). The movements of individual fish have been studied in relation to acoustic stimuli, water-flow in the vicinity of turbine intakes, warps, netting and a midwater trawl. The shape of some fish shoals has been determined, and estimates made of the number of fish in them. The movements of shoals have been followed in relation to each other and in relation to water currents. Observations have been made of a pelagic trawl and a bottom trawl. And there can be no doubts concerning the use of sector scanning for wreck detection and bottom survey work. Figures 68 and 69 suffice to show the sort of detail that can be obtained with this sort of equipment in fisheries work.

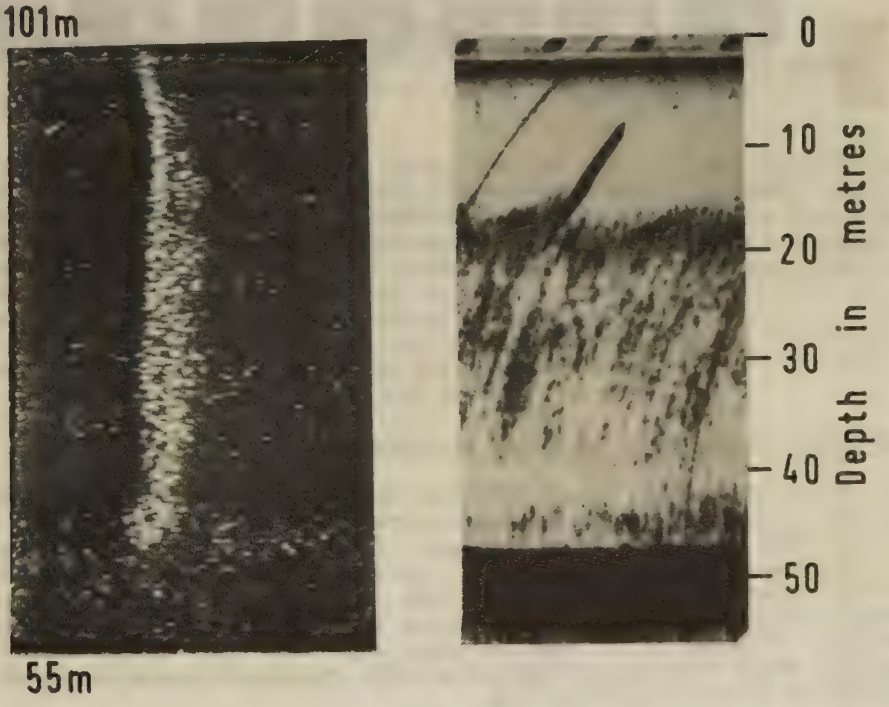


Figure 68 - A plume-shaped school recorded by vertical echo sounder and the Bifocal equipment. The sector scanner gives the plan projection of the school which is long and narrow. The Bifocal display shows that the school is made up of separate units, which may be individual fish. The school is probably pilchards (Cushing and Harden Jones; 1966).

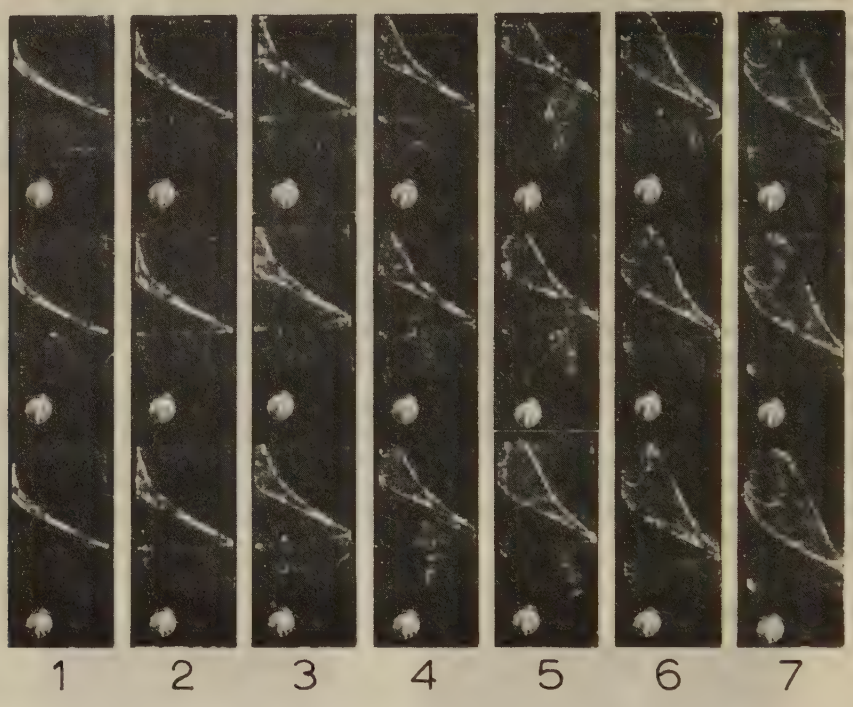


Figure 69 - A midwater, Engel trawl as recorded on the display of the Bifocal equipment at a mean range of 100 m. The individual frames represent consecutive scans of the sector at a repetition rate of four per second and should be read vertically in column 1, up to the top of column 2, down and upto the top of column 3, etc. The vessel with the sector scanner is closing the range on the trawl (Note that headline and footrope are displayed on the last frame of column 7).

1.4 Possible future applications of sector scanning sonar in fisheries work

Although the results of the trials conducted so far have been very promising, the sector scanning sonar is till in its early stages as a fisheries research tool and there must be further extensive trials before its full potential can be assessed. For example, in the sea trials with the Bifocal equipment, scanning was confined to the horizontal plane, when the display gives what amounts to a plan view of the sector. Trials have not yet been carried out with scanning in the vertical plane or with the Bifocal equipment transmitting vertically as an echo sounder, and scanning fore and aft, or athwart, the ship. Scanning in the vertical plane might show fish lying close to the bottom and ahead of the ship, while scanning in the echo sounder mode would remove doubts as to the position of a fish in the beam and so facilitate counting.

For scanning in the vertical plane, the transducer would be turned so that the long axis of the array lies in the vertical plane and is tilted at an angle, say 45°, so that the fan-shaped beam would strike the sea-bed ahead of the ship. What was the vertical beam in horizontal scanning now spreads from port to starboard, and the scanned sector covers a trapezoidal area of the sea-bed which expands with range. The geometry of the system when used in this mode is shown in Figure 70.

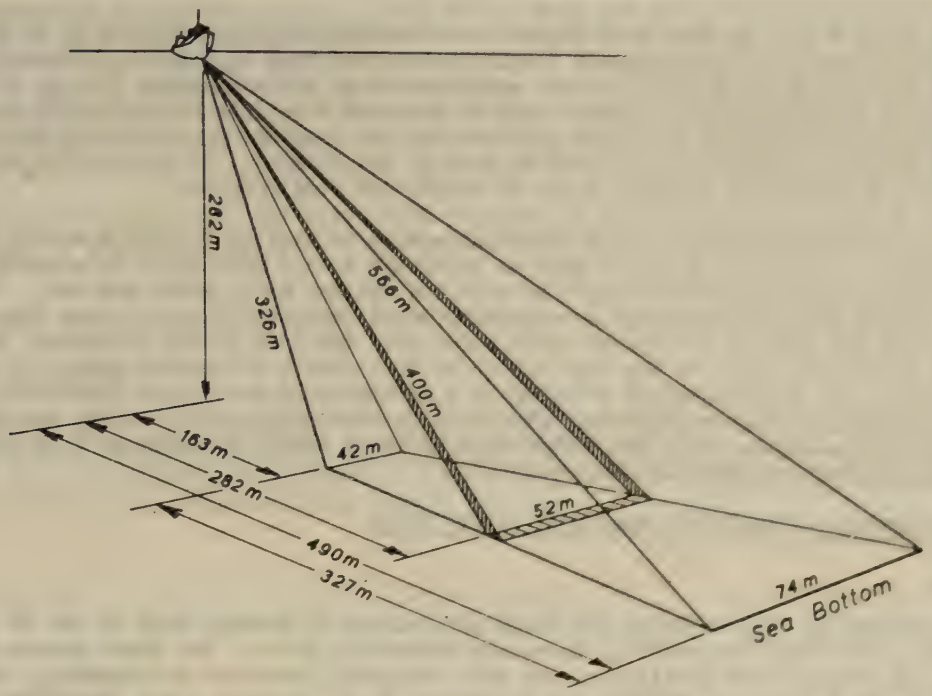


Figure 70 - Vertical scanning for forward search. The geometry of the system with the transducer inclined at 45° to the vertical and with a mean slant range of 400 m

The acoustic mosaic now runs from left to right, rather than up and down, and close to the sea-bed, bottom reverberation could make the detection of a small target, say a single fish, difficult or impossible. The position is shown diagrammatically in Figure 71 which represents one receiver beam width (0.33°) close to the bottom at a slant range of 400 m, and a tilt angle of 45° to the vertical. This beam is on the midline of the scanned sector and is divided, normal to the slant range, into range gates of 8 cm, the receiver beam width at 400 m being 240 cm.

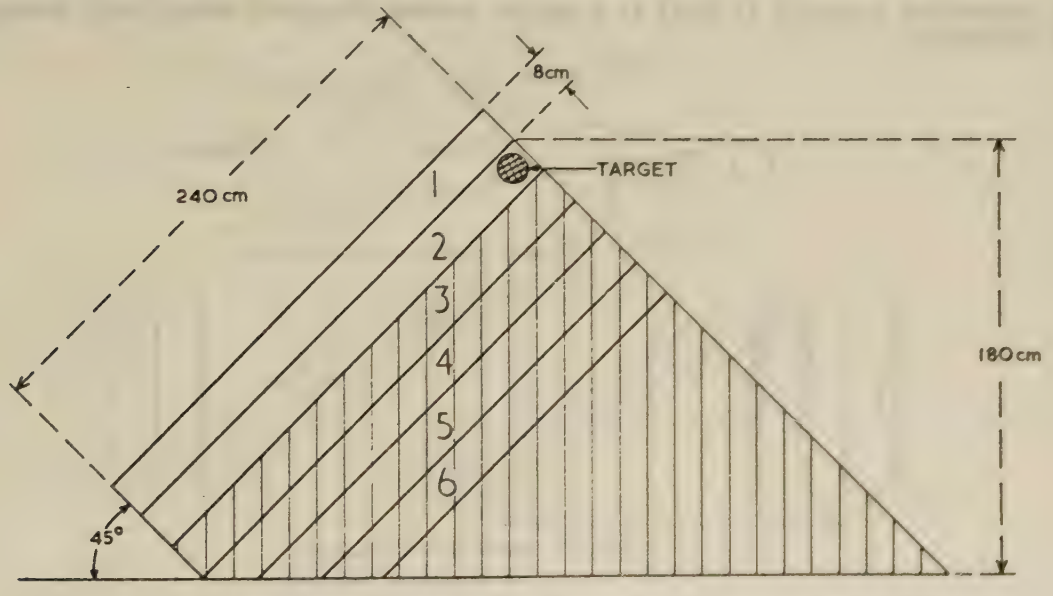


Figure 71 - Diagram (not to scale) showing the height above the sea-bed, of a target from which an echo would be received free from bottom reverberation at a slant range of 400 m and transducer tilt angle of 45°.

Compartments 1 and 2 will be free from bottom reverberation, but compartments 3, 4, 5 and 6 etc. will not. A target at the top of compartment 2 will be detected free from bottom reverberation at a distance of about 180 cm off the bottom. In the compartments at extreme ranges (163 m, 60°; 490 m,30°) the distance from the bottom at which targets could be detected free from reverberation are 105 and 300 cm respectively. These figures give some guide as to what might be expected from vertical scanning with an equipment whose parameters were similar to that of the Bifocal. It is possible that a sonar combining vertical and horizontal scanning might be useful for some purposes.

One problem which has hitherto received little attention is that of fitting a sector scanner into a ship. To be effective the limited sector must be trainable over a wide angle in azimuth and with narrow receiver beam widths stabilization must be provided against roll, pitch and yaw. If the equipment is to be used when the ship steams at a reasonable speed (say over 3 knots) some form of dome may be required to reduce the adverse effects of water noise over the face of the transducer and to protect it from damage by driftwood, etc. If the dome has to be more than a streamline cover, it may have to be big enough to house the space envelope occupied by a mechanically stabilized transducer. It is clear that these requirements could raise important issue in ship construction and design, and thought should be given to these problems at an early stage when layouts could easily be designed to accommodate a scanner and its associated equipment at a later date.

2. CONTINUOUS TRANSMISSION FREQUENCY MODULATED (CTFM) SONAR

2.1 Basic system

A type of sonar system that recently has found application in fishery work is the FM (frequency modulated) or CTFM (continuous transmission frequency modulated) sonar. The basic system uses separate transducers for transmission (projector) and echo reception (receiver hydrophone). The projector typically has a wide beam pattern - perhaps 25° horizontal by 20° vertical - and "isonifies" a large volume of water. The receiver hydrophone has a narrow beam pattern - perhaps 3° horizontal by 10° vertical - to provide good bearing resolution. The projector transmits continuously so that all the targets within its beam are insonified at all times. By scanning with the receiving hydrophone these targets can be detected immediately without waiting (as is the case with a pulsed sonar) for the sound to make a round trip. In practice both projector and receiver hydrophones are scanned to cover a large sector. The scanning rate can be very rapid and is limited by the horizontal beam width of the projector and the doppler shifts across the faces of the hydrophones. In operational systems this is usually about 25° per second and the effects of doppler shift can be minimized with the addition of the "oron doppler nullifier".

The transmitted frequency is swept in a regular pattern (frequency modulation), typically a sawtooth (Figure 72).

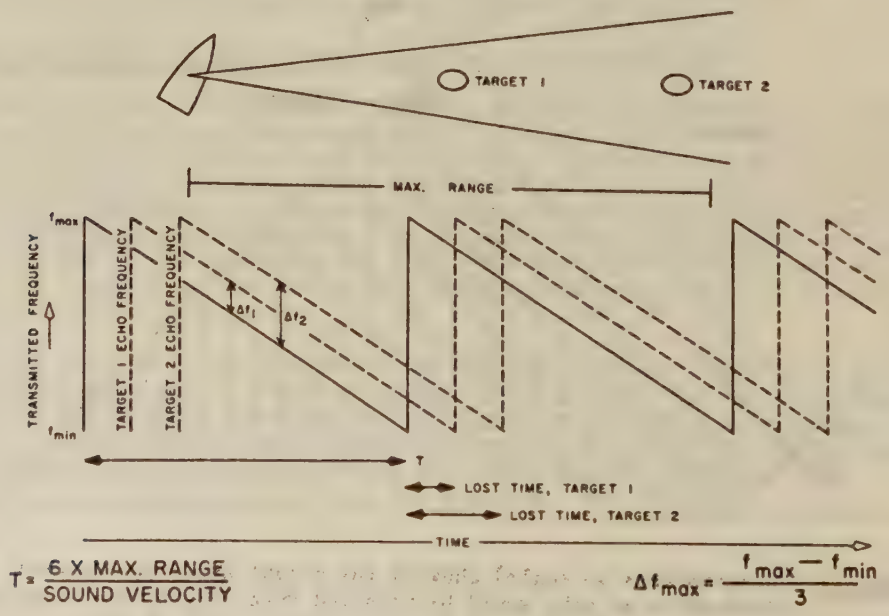


Figure 72 - Principles of CTFM sonar.

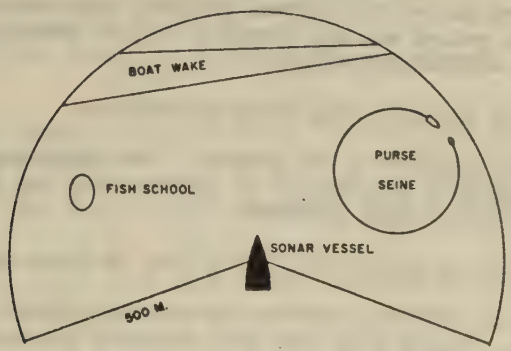
The frequency of the target echo (f_r) will differ from the transmitted frequency (f_t) by some difference frequency (Δf) that is proportional to target range. The transmitted frequency is swept over a range of a few kHz. For example, a CTFM sonar might have a fundamental frequency of 50 kHz. The modulation range is usually designed to be three times the Δf band; if a Δf_{max} of 5 kHz is chosen then the transmitted frequency should be swept 15 kHz, or from 57.5 kHz down to 47.5 kHz. Targets at maximum range would be detected only during the last part of each sweep and the first portion of the sweep is "lost time". This is proportional to range. However, it can be eliminated with appropriate circuitry.

In the receiver electronics the difference frequencies (Δf's) are detected by a frequency analyzer; range resolution is limited by the number of filters - thus time constants and the hydrophone scanning rate.

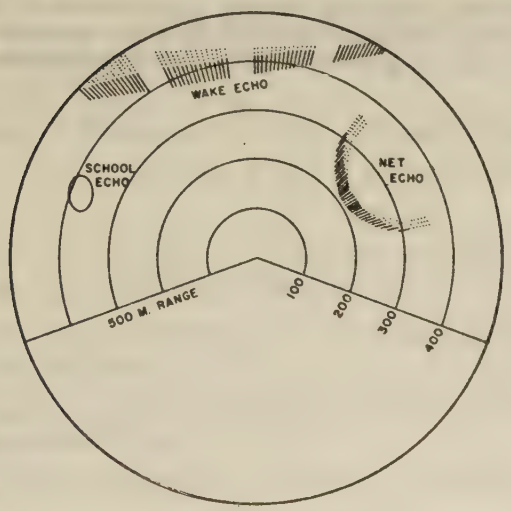
This gives a range resolution of 1.0 m at 100 m or 16.0 m at 1,600 m maximum range.

2.2 Display of targets

The output of the frequency analyzer is changed to a video signal and presented as an intensity-modulated trace on a cathode-ray-tube. Targets appear as bright spots displaced along the trace in increments of range on a PPI display which is easily interpreted by anyone familiar with radar displays. This is shown diagrammatically in Figure 73.



HYPOTHETICAL SONAR TARGETS



PPI DISPLAY OF ABOVE

Figure 73 - Diagrammatic representation of targets on CTFM sonar, PPI display.

Targets are also presented audibly. Since the Δf band lies in the audio range, further signal processing is unnecessary and target Δf can go directly to a loud speaker or headset.

Fish and floating objects generally give a much clearer sound and video display than the bottom. Schools of small fish (sardine, anchovy) have a clear, bell-like echo against the falling tone of the transmission reverberations and make a bright spot on the CRT. Schools of large fish (tuna) generally have a scratchier echo and fuzzier video: the targets often disappear and reappear as the aspect of the school changes in relation to the beam. At close range (less than 100 m) large fish resolve into separate spots on the scope whereas small fish do not.

2.3 Additional optional features of CTFM sonars

Sonar systems are designed as compromises among various factors of range, resolution, size and cost. CTFM systems can be designed to have long-range detection capability, excellent resolution, and small physical size - but such systems are extremely expensive. For fishery work, cost is important and can be kept down by using minimal systems. If the cost is not of primary importance, however, a number of options can be included to increase the performance of the system. A basic CTFM system similar to the one described in the first part of this discussion can be built at a price competitive with an advanced pulsed sonar system.

2.4 Applications of CTFM sonar

CTFM sonar systems are best suited for fishery problems that require rapid information flow, e.g. in the deployment of purse seines and the tracking of fast swimming fishes. In these applications CTFM sonars have the following desirable features:

(a) Rapid bearing scan and instantaneous range information

(b) Multiple target presentation on a PPI display. The persistence of the target trace on the cathode-ray-tube simplified maintenance of contact with the target and provides some indication of probable future target position

(c) Target echo fluctuation is minimized without loss of range resolution.

Since each target is a continuous secondary source its echo is present for the entire time it is in the receiving hydrophone beam path. During this time echo strength fluctuations associated with the path are averaged.

The major disadvantage of CTFM sonar for fishery applications is its limited range because of low transmitted power. Power output is limited primarily by the necessity of continuously driving the projectors and secondarily by cross talk between projector and hydrophone.

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Drafts of "Manual of laboratory methods in fisheries biology" were issued as:

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MI/84679/2.69/E/1/500